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THE OUTLOOK FOR COPPER[1]

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IT should be evident to all by this time that if prosperity does "lie just around the corner" our advisors have failed to tell us where that corner is or else they do not know where it is themselves. In 1928, the copper industry turned the corner leaving prosperity behind and has been heading steadily away from it ever since. However painful the route, at least we could return the same way we went. Probably that is the only way. At all events before floundering any further into the slough of depression or chasing the will-o'-the-wisp of stabilization over a quaking morass, why not study the back trail and see if it is as difficult as it appears. Perhaps many other industries took similar detours in their misguided attempts to stabilize prosperity and abolish hard times. The sum total of such futilities, both by industries and governments, is doubtless why we are where we are.

In a review of the copper industry for the year 1928, written in December of that year,[2] I wrote as follows:

> Extraordinary growth in the copper industry was noted in 1928, the result of a resumption of the strongly upward trend in domestic consumption in effect since 1921. This trend reacted with the decline of general domestic business in 1927. A similar trend in Europe had its reaction in 1926.

[1] Presented before the Society of Economic Geologists, Tulsa Meeting, December 29, 1931.

[2] Eng. and Min. Jour., Jan. 19, 1929.

Under the joint stimulus of activities in both hemispheres, consumption has reached a point where for the time being it is taxing the capacities of the producers to meet the world's need for the metal. The electrical industries, the building trades, and the automobile industry continue to absorb the great bulk of the output, radio and aviation having added a small but rapidly growing demand. Any slowing down in the three major fields of consumption would be reflected promptly in the activity of the copper industry and its prosperity.

World production for 1928 will show an increase of about 15½ per cent over that of 1927. North and South American output will be about 16½ per cent greater. The following group of twenty North and South American companies owned in the United States has produced between 63 and 65 per cent of the world's output each year since 1923. They are now producing at the rate of about 2,900,000,000 lbs. per annum, an increase of nearly 35 per cent over their production in 1927. Exact figures for the calendar year 1928 are not yet available. They will probably show some small increase in their proportion of the total. The twenty companies comprise: Anaconda Copper; Andes Mining; Calumet & Arizona; Calumet & Hecla; Cerro de Pasco; Chile Copper; Copper Range; Granby Consolidated; Greene Cananea; Inspiration; Kennecott; Magma; Mohawk Mining; Miami Copper; New Cornelia; Nevada Consolidated; Old Dominion; Phelps Dodge; United Verde Copper and United Verde Extension.

For the first time in nine months stocks of refined copper in North and South America showed, on Dec. 1, 1928, an increase over the figures for the previous month, according to the American Bureau of Metal Statistics. The amount of this increase was 6,500 tons. The total was then 52,153 tons, a reduction of 44,323 tons since Jan. 1, 1928. *It is too early definitely to forecast a change of trend, but at least a warning bell has sounded, and in spite of the immediate prospect of sustaining consumption at an unprecedented rate, it would seem hazardous to project this rate very far into the future.*

Total stocks of blister and refined copper in North and South America, Great Britain, Havre, and Japan, according to the same authority, have fallen to about 35,500 tons since Jan. 1, 1928, and increased about 8,270 tons during November, 30 per cent more than the increase in refined stocks alone. The ability of the industry to respond to such demands is convincing proof of its sound and intelligent organization. Use has been found, for the present at least, for the tremendous expansion of capacities stimulated by the war. That expansion, coupled with misapprehension on the part of the producers of the fundamental facts of the industry, had kept it unduly depressed ever since the armistice until the second half of 1928. The lessons from adversity are usually bitter, but generally whole-

some. Enlightened self-interest has apparently taken hold of the situation, to the benefit of producers, consumers, employees, stockholders, and the general public. It is well to remember, however, the homely fable of the dog with the bone in his mouth, who, on seeing his image reflected in the water of the pond, opened wide his jaws to grasp the image of the bone he already had, and, in doing so, lost both the substance and the shadow.

Since this warning bell was sounded, the total stock of refined and blister copper, as reported by the American Bureau of Metal Statistics, had increased to 705,685 tons on October 1, 1931, an all time record. Since then no figures have been published by the Bureau. It is safe to assume, however, that they are no better and have probably been added to by some 50,000 tons. With these record breaking stocks and a record breaking low price, the industry has lost both "the substance and the shadow" of the prosperity well within its grasp in 1927 and 1928.

The following tables, Nos. I and II, illustrate the history of the relationships between production, selling price, distributions to creditors and owners in bond interest and dividends, and the percentage of the selling price that has been distributed.

Table I covers the Michigan industry alone, as only Michigan figures are available for the full period from 1861–1910; Table II takes up the story at that point and brings it down to date as measured by a group of companies that produced from 55 to 65 per cent. of the world's total in each of the 5-year periods shown.

Table I shows a record of continuous growth in production, and an almost continuous expansion in the volume of profits returned to the owners. It shows also a continuous decline in the average price, up to the period ending with 1895. For the next 15 years to the close of 1910 it rose again. One is forced to the conclusion that almost throughout this 50 years, the cost of producing copper in the Michigan district was steadily falling. This is undoubtedly true for the first 35 years. The most significant point is the relative constancy of the percentage of the selling price that was distributed to the owners. Aside from the first 10 years, when the difficulties of the Civil War upset conditions, this percentage never fell below 21.2 per cent. in any period, and only once rose

above 30 per cent. and for the whole 50 years averaged 25.4 per cent.

Table II shows a similar trend in the growth of production, somewhat disturbed by the effects of the Great War. Prices have been even more disturbed. Changes in volume of distributions also reflect these disturbances, but the percentage of the selling price represented by the distribution for the last twenty years has been 26.8 per cent., with a variation from 23 to 30 per cent. This is in entire accord with the previous history. It seems certain that this proportion represents the normal economic ratio between price and profit and consequently a normal economic ratio between total cost and price of 75 per cent., less whatever earnings have been put back into the business for expansion. The distributions per pound of metal in Table I averaged 3.86 cts. and in Table II 4.52 cts. Here again we see strong evidence of an economic balance of about 4 cts. a lb. as the normal margin. Careful study of the records indicates that in addition to the 4cts. about 1 ct. a lb. has been re-invested in the industry and, together with new capital supplied by the public, has enabled this section of the industry to expand its capacity over 100 per cent. in the last 20 years.

TABLE I. MICHIGAN INDUSTRY.

Period.	Production Pounds (000 omitted).	Average Selling Price Per Lb.	Bond Interest and Dividends Paid.		% of Average Selling Price Paid out in Bond Interest and Dividends.
			Total (000 omitted).	Per Lb.	
		Cts.		Cts.	%
1861–65.....	68,605	33.58	3,080	4.48	13.4
1866–70.....	103,448	24.48	1,290	1.24	5.1
1871–75.....	150,965	25.58	10,910	7.22	28.2
1876–80.....	211,375	18.70	10,449	4.95	26.5
1881–85.....	312,208	15.18	11,482	3.68	24.2
1886–90.....	433,005	13.75	12,615	2.91	21.2
1891–95.....	593,666	10.75	15,980	2.69	25.0
1896–00.....	721,829	13.84	38,403	5.32	38.4
1901–05.....	957,136	14.30	30,574	3.19	22.3
1906–10.....	1,121,800	15.77	45,499	4.06	25.7
	4,674,037	15.21	180,302	3.86	25.4

TABLE II. AMERICAN-OWNED INDUSTRY IN NORTH AND SOUTH AMERICA.[3]

Period.	Production Pounds (000 omitted).	Average Selling Price Per Lb.	Bond Interest and Dividends Paid.		% of Average Selling Price Paid out in Bond Interest and Dividends.
			Total (000 omitted).	Per Lb.	
		Cts.		Cts.	%
1911–15.....	5,420,000	15.37	202,860	3.74	24.3
1916–20.....	8,250,000	23.35	520,140	6.30	27.0
1921–25.....	7,119,100	13.64	223,600	3.14	23.0
1926–30.....	11,234,000	14.89	501,800	4.47	30.0
	32,023,100	16.87	1,448,400	4.52	26.8

TABLE III.

Years.	Production Pounds (000 omitted).	Average Selling Price Per Lb.	Bond Interest and Dividends Paid.		% of Average Selling Price Paid out in Bond Interest and Dividends.
			Total (000 omitted).	Per Lb.	
		Cts.		Cts.	%
1921.....	520,100	12.50	19,200	3.69	29.5
1922.....	1,064,000	13.38	23,100	2.17	16.2
1923.....	1,581,000	14.42	61,700	3.90	27.0
1924.....	1,924,000	13.02	55,000	2.75	19.6
1925.....	2,030,000	14.04	64,600	3.13	22.6
1926.....	2,114,000	13.86	75,000	3.55	25.7
1927.....	2,156,300	12.92	82,500	3.82	29.6
1928.....	2,463,400	14.57	94,900	3.85	26.4
1929.....	2,689,600	18.11	159,400	5.93	32.7
1930.....	1,810,700	12.98	90,000	4.97	38.3
	18,353,100	14.40	725,400	3.95	27.4
ESTIMATE FOR 1931.					
1931.....	1,700,000	8.25 cts.	45,000	2.65 cts.	32.1%

Here we begin to approach the corner which the industry turned late in 1928. To understand the situation we must examine the course of events more in detail. Table No. III is similar to Tables I and II, but gives the figures by years for the last ten years.

In Table III again we see the growth of production and distribution from the trough of the primary post-war depression in 1921. However, this growth took place in three steps, rising

[3] Includes companies previously referred to which have produced 55–65 per cent. of world's total output in each of years 1923–1930 inclusive.

from half a billion pounds in 1921 to nearly two billion in 1924, then slowly increasing to two billion 140 million in 1927, and finally rising sharply in 1928 and 1929 to nearly two and three-quarters billions in the latter year. Distributions show a somewhat parallel growth, with this important difference that whereas production more than quadrupled in the first two steps, distributions increased only 3.6 times. In the third step, however, based on 1929 figures, whereas production increased about one-third over the second, distributions doubled. Here we are face to face with the corner. What had happened? The price had jumped from 14 cts. in April 1928 to 15¾ cts. early in December, and early in March had been pushed to the absurd level of 24 cts. per lb. in the face of a still present surplus of capacity. As a matter of fact, curtailment was inaugurated again in April to meet declining demand, and the price was pegged at 18 cts. What warnings were there of impending collapse? We have already referred to two of them, an increase in the stocks of unsold metal reported on December 1, 1928, the first increase in nine months. Any hysteria on the part of buyers could have been readily dispelled by a concerted frank statement of the facts by the producers. Secondly, the rate of increase in production was entirely unprecedented, and could not be expected to continue. In addition, the volume of earnings had sky-rocketed to dizzy heights never before approached. The tables tell this story unmistakably by all three measures: (1) the volume of distributions, (2) the distribution per pound, and (3) the percentage of the selling price distributed (see 3 last columns of Table III.).

Still unconvinced of its error, and unheedful of declining general business, increasing stocks of unsold metal, rising interest rates and the final collapse of security prices late in 1929, the industry persisted in maintaining a price providing a margin of profit never before yielded by the industry, excepting during the war, at much higher levels of cost and price. This price was held until April, 1930, when it too collapsed. Since then with one brief interlude in the late fall of 1930, it has drifted steadily lower while unsold stocks have risen higher and higher. The

price recently settled to the all-time low at 6½ cts. in the New York market, and stocks of unsold metal are at an all-time high.

There were certain developments within the industry in the critical years 1926–1930 which have played an important part in the drama. On the background of an industry over-developed by the high war prices, still further expansion of already existing capacities and the exploitation of new deposits were inaugurated in various parts of the world.

The rôles of the members of the particular group of companies which we have been studying is summarized in Table IV.

TABLE IV. DISTRIBUTION OF PRODUCTION BY GROUPS FOR CRITICAL YEARS 1927–1930 INCLUSIVE IN POUNDS (000 OMITTED)

Company.	1927.		1928.		1929.		1930.	
	Amount.	%.	Amount.	%.	Amount.	%.	Amount.	%.
Anaconda	203,910		233,746		281,938		185,324	
Andes	54,376		104,058		162,664		94,046	
Chile	219,600		265,864		299,576		179,192	
Greene Can	28,738		36,420		58,826		42,424	
Inspiration	88,458		88,124		107,308		65,862	
Sub Total	595,082	27.5	728,212	29.6	910,312	33.8	566,848	31.3
Kennecott	34,744		28,000		28,182		22,990	
Utah	233,002		273,824		296,626		161,138	
Braden	202,968		218,272		176,326		161,986	
Mother Lode	20,588		13,418		12,242		9,646	
Nevada	218,684		268,462		266,274		141,980	
Sub Total	709,986	32.8	801,976	32.6	779,650	29.0	497,740	27.5
Phelps Dodge	185,358		204,984		219,250		141,662	
Cal. and Ariz	48,164		50,732		127,140		87,380	
New Cornelia	72,932		77,996		included		in Cal. and Ariz.	
Sub Total	306,454	14.1	332,712	13.5	346,390	12.9	229,042	12.6
Calumet and Hecla	120,154	5.6	131,724	5.3	134,694	5.0	116,398	6.4
Cerro de Pasco	90,446	4.2	98,064	4.0	99,986	3.7	86,000	4.7
Miami	53,038	2.4	48,260	1.9	58,842	2.1	67,124	3.8
United Verde	99,490	4.6	118,112	4.8	142,290	5.2	70,720	3.9
United Verde Ext.	41,302	1.9	45,200	1.8	64,112	2.4	45,568	2.5
All others in Group	150,344	6.9	159,194	6.5	162,296	6.0	131,278	7.3
	2,156,296	100	2,463,454	100	2,689,572	100	1,810,718	100

Of the total increase in 1929 production over that of 1927, amounting to 533,276,000 lbs., the Anaconda group was responsible for 315,230,000 lbs. or 59.1 per cent. Two-sixths of this was the result of bringing the Andes Company into production. The initial production from this property came in 1927. Three-sixths came from equal increases at Butte and Chile, and the remaining one-sixth from Greene Cananea and Inspiration.

The Kennecott group was responsible for only 10.3 per cent. of the total; Phelps Dodge for 7.5 per cent. and the balance of the group, 24.1 per cent.

Anaconda increased its proportion of the total output from 27.5 per cent. in 1927 to 33.8 per cent. in 1929. Kennecott dropped from 32.8 to 29 per cent. and Phelps Dodge from 14.1 to 12.9 per cent. All others combined dropped from 25.6 to 24.4 per cent.

Outside of the Group, Canada increased its output from 141,400,000 lbs. in 1927 to 242,000,000 lbs. in 1929 and 352,000,000 in 1930, mainly from new developments in Noranda, International Nickel and Hudson Bay Mining and Smelting Co. The Belgian Congo-Katanga production was stepped up from 196,000,000 lbs. in 1927, about the average of the previous three years, to 302,000,000 lbs. in 1929 and 308,000,000 in 1930. In the aggregate these increases brought world output from 3,365,000,000 lbs. in 1927 to 4,254,000,000 in 1929 and 3,500,000,000 in 1930.

In addition to all these developments, the industry in 1929 was face to face with the imminent exploitation of perhaps the largest copper field in the world in Northern Rhodesia. Published plans in 1928 and 1929 of the English and American interests in control of this field contemplated adding a further 1,000,000,000 lbs. per annum to the world supply by 1935 with the initial output to come in 1931.

Certainly no one can now seriously contend that the price policy yielding an unprecedented margin of profit, namely 18 cts., was anything but the height of folly in view of this situation, and yet it was stubbornly maintained for a whole year after business had

actually started to decline in March, 1929, and even for six months after the collapse of the stock market balloon in October of that year.

At the close of 1927, the Anaconda Company had outstanding $248,770,000 of fixed obligations of its own and its subsidiaries with annual interest charges aggregating $13,700,000. By the end of 1929, it had cleared from the books by retirement or conversion all but $37,182,000 of this amount. These constituted the sole fixed obligations of the group both in 1927 and 1929. There can be no doubt that the 18 ct. price was a great aid in accomplishing this result. Neither can the result be questioned from the Company's standpoint. Many other corporations, notably the U. S. Steel Corporation, took similar advantage of the opportunities afforded by the boom to rid themselves of their debts.

Let us turn now to the stock market aspect of the industry and see how the owners of the industry have fared through this stormy period. Table V. is reprinted from an interview in the Wall Street Journal under date of October 30, 1931, with the addition of the stock market value of all outstanding securities adjusted for duplication at the closing prices for Monday, December 21, 1931. The group of companies included is the one we have been considering throughout this study.

At the lows for this year reached in December, this section of the industry was selling for 40 per cent. of the figure reached in the 1920 lows and for less than 9 per cent. of the highs reached in 1929. Both extremes are absurdities.

The companies will probably finish the year with about $200,000,000 in net current assets leaving $100,000,000 as the market value of the mines and plants. On the basis of the cost of developing and equipping copper properties during the last 20 years, it would require an investment of over $700,000,000 to duplicate the present capacities of these properties, given the ore bodies.

This cash position is about that reached at the trough of the depression in 1921, when a general shut down of production started the industry solidly on its way back to normal. Doubtless

TABLE V.

Year.	Market Value of All Outstanding Securities Closing Quotations Dec. 31 Each Year (000 omitted).	Bond Interest and Dividends Paid During Year (000 omitted).	Yield Based on Bond Interest and Dividends Paid During Year.	Average Selling Price of Copper per Pound.
			%	Cts.
*1931, Dec. 22....	$366,000	*$8,320	†2.27	8.25
1931, " lows...	300,000	.....	....	.....
1930, ...	754,000	90,000	11.93	12.982
1929, ...	1,803,000	159,400	8.84	18.107
1929, highs.....	3,351,000	.....	4.76	.....
1928, ...	2,439,000	94,900	3.88	14.570
1927, ...	1,144,000	82,500	7.12	12.920
1926, ...	1,140,000	75,000	6.58	13.795
1925, ...	1,142,000	64,600	5.67	14.042
1924, ...	1,160,000	55,000	4.74	13.024
1923, ...	959,000	61,700	6.43	14.421
1922, ...	876,000	23,100	2.64	13.382
1921, ...	913,000	19,200	2.10	12.502
1920, lows.....	700,000	12,200	1.74	17.456
11 year total (1920–30 incl.)	§.....	737,500	....	
Annual Av'ge....	.....	67,500	‡22.5	

Companies included in group are Anaconda, Andes, Chile, Greene, Inspiration, Calumet & Arizona, Phelps Dodge, Kennecott, Nevada, Mother Lode, Calumet & Hecla, Cerro, U. V., U. V. X., Granby, Miami, Magma, Mohawk, Old Dominion, Copper Range.

The figures for market values and bond interest and dividends have been adjusted for duplications due to ownership of securities by members of the group. All fixed obligations have been valued at par.

it has had a very stimulating effect in bringing about the recent change of front.

In the last week it has been announced that the industry does not intend to continue producing what the world can not use at present at a price which spells ultimate bankruptcy for the entire industry.

Let me close with just a word about the tariff agitation. First of all, those producers who are now asking for help from the

* Current rate of disbursements to bond and stockholders after giving effect to all reductions and omissions announced up to December 15, 1931. The amount for the year will be in excess of $50,000,000.

† Estimated. ‡ On December lows. § Omitting 1931.

public's pocket, never raised a protest against the unwarranted profits that poured into their treasuries in 1928 and 1929, any more than they did over the war profits. They were all willing parties to the price policy that allowed their potential competitors in South America, Africa and Canada to expand and occupy the foreign market. Secondly, there is just as great an excess of domestic capacity over probable normal domestic consumption as there is of foreign capacity over probable foreign consumption. Consequently, a tariff can not be made effective without a conspiracy among the domestic producers to withhold output. Fourthly, if such a conspiracy were legal, it could not be enforced among companies whose costs vary from 5½ cts. to 12 cts. per lb. to produce the metal. In fact, a tariff would do the domestic industry just about as much good as a tariff on wheat did the wheat farmer. A 43 ct. tariff on wheat brought 45 ct. wheat. By analogy a 4 ct. tariff on copper might be expected to bring 4½ ct. copper. As much might be said for sugar and many other products. It has been stated on good authority that the late Smoot-Hawley bill raised the tariff on some 800 articles; it would be pertinent to ask how many of those have escaped the depression. The steel industry which has always been protected is reported to be operating at about 26 per cent. of capacity. The program just announced for the copper producers calls for 26½ per cent. of capacity.

It should be remembered that the ownership of 75 per cent. of the World's copper industry rests in American hands. This is unique with respect to the raw materials of the mineral industry in wide use. All the companies now appealing for help from the public pocket-book had an equal opportunity to secure an interest in these foreign resources with those who were successful in so doing. Had they done so, there would be no tariff agitation now.

Let me quote now the views of an old friend and a distinguished authority on the economics of the mining industry, Mr. J. R. Finlay:

> One thing that has always astonished me is the failure of the United States to recognize what is meant by a 'favorable balance of trade'. Its

current idea seems to have been inherited from the long decades during which we were a debtor nation when an excess of exports over imports went to pay for our debts and maintained our credit, but that is a time already long past and we have become the principal creditor nation of the world. If our foreign credits are to be worth anything we must have an excess of imports over exports. . . . Then the folly of creating prosperity by restricting trade on the part of nearly all the nations; the adoption of schemes discredited by all former experience in the direction of stabilizing prices, stabilizing employment, prosperity, etc. This tariff agitation for copper is just another example of the crowning vice of this country. Namely that small interested minorities by force of clamor and publicity succeed so often in putting over schemes that are absolutely contrary to the public interest. It almost seems as if we are becoming a nation of beggars, indulging in the folly of begging from ourselves, for that is all it amounts to.

In large measure the industry must bear the burden of its own short-sighted greed. It is an American industry, regardless of where its investments lie. Its over-development and present prostration are the direct result of attracting new capital into the industry at too fast a rate. The lures to the investor were the undue profits realized from war conditions, followed ten years later by " stabilization at 18 cents."

The only sure correction is a period of low prices, which will discourage further expansion, lessen serious competition by other metals in its fields of use and encourage consumption by intelligent cultivation of the interest of the consumer. Faithfully pursued, this policy will result in profits to the industry over the next decade, comparable with those of the past. Any artificial restraints such as the proposed tariff, if effective in raising prices, will merely repeat the results of past high prices and thereby defeat their own ends.

New York City,
December 29, 1931.

THE ECONOMIC RELATION OF GEOPHYSICS TO GEOLOGY ON THE GULF COAST.[1]

J. BRIAN EBY.

THE finding of more than sixty domes on the Gulf Coast of Louisiana and Texas during the last eight years by geophysical instruments has been an impressive achievement. It is all the more remarkable in view of the fact that all previously known domes on the Coast numbered but forty-seven.

The purpose of this paper is to review briefly this contribution of geophysical research to the mineral exploration of the Gulf Coast. The present and probable future status of geophysics on the Coast is discussed and an attempt is made to relate the geophysical expenditures with the increased mineral valuations, both actual and potential, obtained by these methods.

To represent graphically the notable results of geophysical exploration, Fig. 1 is presented, showing the chronological arrangement of all dome discoveries on the Texas and Louisiana Gulf Coast. Appropriate symbols show those structures located by geology, torsion balance and seismograph, and whether or not they are oil-producing. The areal distribution of these domes and other Coastal producing fields is shown in Fig 2. The territory primarily considered in this paper, however, is that portion of the Coast from the Colorado River of Texas to the Mississippi River, and within 125 miles of the Coast. All producing fields in this area are here considered of salt dome origin whether salt has actually been drilled into or not.

In order to develop the present position of geophysics on the Coast the early salt dome history of the area is briefly reviewed.

The discovery of the famous Spindletop Oilfield near Beaumont, Texas, on January 10, 1901, focused world attention on

[1] Presented before Section E, Geology and Geography, American Association for the Advancement of Science, January 1, 1932, New Orleans, La.

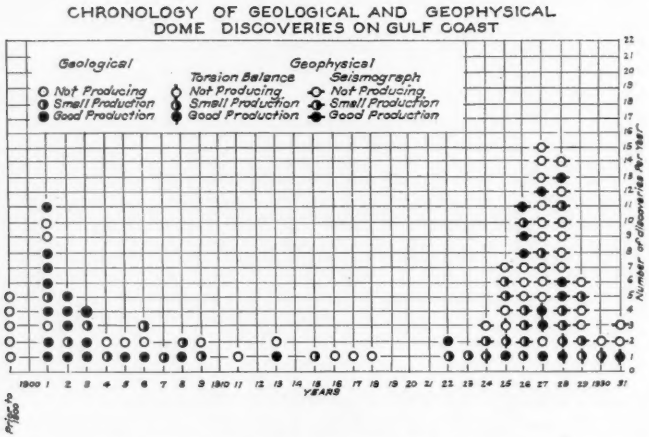

FIG. 1. Chronology of geological and geophysical dome discoveries on Gulf Coast.

Names as listed below correspond to Symbols reading up.

1900: Belle Isle, Cote Blanche, Weeks Island, Avery Island, Jefferson Island; **1901:** Spindletop, Damon Mound, Bryan Heights, West Columbia, High Island, Hackberry, Saratoga, Pierce Junction, Big Hill—Jeff., Big Hill—Mat., Jennings; **1902:** Barbers Hill, Piedras Pintas, Sour Lake, South Liberty, Vinton; **1903:** Batson, Sulphur, Welsh, Blue Ridge; **1904:** North Dayton, Hoskins Mound; **1905:** Humble, Davis Hill; **1906:** Goose Creek, Hockley, Bayou Bouillion; **1907:** Anse LaButte; **1908:** Hull, Markham; **1909:** Edgerly, Pine Prairie; **1911:** Gyp Hill; **1913:** Orange, Stratton Ridge; **1915:** Brenham; **1916:** Palangana; **1917:** New Iberia; **1918:** Section Twenty eight; **1922:** Big Creek, Lockport; **1923:** Boling; **1924:** Nash, Orchard, Long Point; **1925:** Sweet Lake, Allen, Clemens, Hawkinsville, Fannett, Starks, Arriola; **1926:** Clay Creek, Bayou Blue, Sorrento, Moss Bluff, Napoleonville, Fausse Point, Bayou Des Glaise, Whitecastle, Port Barre, Bayou Choctaw, East Hackberry; **1927:** Raccoon Bend, Alta Verde, Hankamer, Sugarland, Chacahoula, Darrow, Brookshire, Lost Lake, Calcasieu Lake, Vermilion Bay, Dog Lake, Black Bayou, Four Isle, East Bayou Junop, Bay Saint Elaine; **1928:** Esperson, Mykawa, Lake Washington, Caillou Island, Lake Pelto, Lake Barre, Lake Salvador, Venice, Leesville, Potash, Port Neches, Lake Hermitage; **1929:** Manvel, Iowa, Fergusons Crossing, Danbury, Cameron Meadows, Gueydan; **1930:** Sheppards Mott, East Stratton Ridge; **1931:** Rabb Ridge, Minor Estate, Stratton.

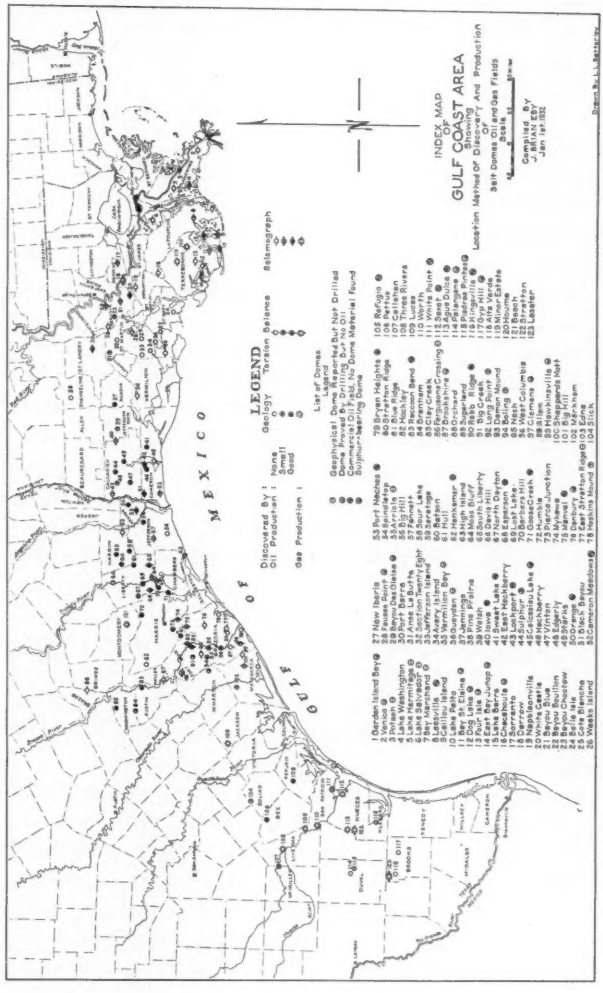

FIG. 2. Index map of Gulf Coast area, showing location method of discovery and production of salt domes and gas fields.

the oil-producing possibilities of the Gulf Coast. It was learned from the geologic structure of this field that the oil accumulated in beds overlying rock salt occurring in the shape of a pipe or stock. To such a buried salt mass the term " dome " is commonly applied.

At Spindletop the buried dome is reflected at the surface by mounding or topographic elevation. This mounding at once became one of the principal criteria for the finding of other domes. Geologist and wildcatter hurriedly scoured the Coast, and in the remaining months of 1901 found and confirmed by drilling eleven other similar structures, nine of which produced oil from the start.

Once, however, the more obvious surface indications had been drilled, the geologic examination of the Coast became more difficult. Minute oil or gas seeps were inspected, stained or paraffined earths and contaminated waters were analyzed, and peculiar drainage patterns were studied. By 1905, twenty-nine domes were discovered, seventeen of which were producing, including especially the notable Humble Field in Texas, and the Jennings Field in Louisiana. The peak of the early Coast production was reached that year, nearly forty million barrels, an annual production not again surpassed until twenty years later.

The following sixteen years, or to the close of 1923, were lean years for the geologist and the wildcatter. Seventeen domes were located, ten of which produced oil with nominal development. The increasing hazard of drilling on less and less distinct surface indications now exceeded a reasonable hope of success.

Such was the situation on the Gulf Coast at the beginning of the 1920 decade. The geologist found that he had nearly exhausted the possibilities of his time-honored methods of exploration and discovery on the Coast. The stark futility of further drilling without reasonable geologic guidance was pointed out by one Coast geologist,[2] who stated that " in the several years following 1917 approximately 675 wildcat wells were put down at an estimated drilling cost of $20,000,000.00, during which one

[2] Henniger, W. F.: Sulphur Waters in the Gulf Coast and their Significance in Locating New Domes. Geology of Salt Dome Oilfields, 1926, page 776.

dome only was discovered." To explore the Coast adequately by wildcat drilling alone would obviously be a matter not only of incomparable expense but of decades and even generations of time.

In order to appreciate the almost spontaneous success of geophysical methods on the Coast it is necessary to understand something of the Coastal formations and structure. The Coastal plain is comparatively flat and the surface rocks are of Quaternary age at the Coast and Tertiary further inland. All the formations dip gently seaward and, as the surface truncates them successively inland, each formation outcrops in a broad belt paralleling the seacoast. In the salt dome region of the Gulf Coast, therefore, all the geologic formations older than the Tertiary, the Cretaceous for example, are buried at great depth variously estimated from 15,000 to 20,000 feet.

This means that all rocks within even remote drilling depths, in the normal structure of the Coast, belong to the youngest beds in the geologic column. These beds, although retaining their original stratification, are in a sense of homogeneous character in being soft, poorly consolidated, and lacking prominent or resistant beds or markers. They consist primarily of clays, shales and packed sands.

The salt domes offer the one abnormality of formation and structure. These massive salt occurrences are found irregularly scattered along the Coast, chiefly from the Colorado River in Texas to the Mississippi River on the East. They are circular to oval in outline and from less than one-half mile in diameter at Sulphur dome, to more than six miles at Boling dome. The salt stock is commonly flat-topped and in most places is capped by limestone, gypsum, and anhydrite.

The salt is generally conceded to have been thrust upward from more extensive salt accumulations at great depth. In rising into and through the younger formations, the overlying sands and shale beds were either domed upwards or faulted, and the edges adjacent to the salt wall were dragged upward. The top of the salt core is found at various depths in the different domes, rang-

ing from surface exposure to a known drilled depth of over 6400 feet. Under some Coastal oilfields the salt has not been reached and may well lie far below possible drilling depth.

The chief function of the salt dome in oil and sulphur accumulation is to cause or provide a suitable reservoir. In the case of oil it may occur in the arched beds over the dome, or within porous caprock of the dome itself or in beds tilted against the salt walls. In the case of commercial sulphur it is found in the porous limestone caprock. It is obviously the fundamental problem of the Gulf Coast geologist to locate the dome accurately, and the duty of the driller to locate the oil and the sulphur.

Many of the Coastal domes give some surface evidence of their existence. On the other hand it is now known that a large number of domes exhibit no surface features. In fact several salt domes now being drilled are covered by vast bays, lakes and featureless marsh. It was in the location of structures such as these that geophysics was to play such a spectacular rôle, and lay the real cornerstone of its commercial success.

Geophysical methods for geologic exploration deal primarily with the measuring or recording of physical phenomena that are direct functions of the physical properties of the various rocks below the surface. Thus the torsion balance measures directly the rate of change of the intensity of gravity. The seismograph measures the velocity of propagation of elastic waves through the various strata. The magnetometer records differences in the earth's magnetic field and by electrical methods are measured the relative electric conductivities of the different formations. Of these various methods, however, only the torsion balance and seismograph have been profitably used in the Coast region.

The topography and geology of the Coast are favorable for the successful application of geophysical methods. The tens of thousands of square miles of level prairie and marsh, underlain by thousands of feet of uniformly soft, poorly consolidated sediments into which are intruded hard rock plugs of salt and limestone, give an ideal setting for geophysical operations. All the physical properties of the salt dome are in striking contrast to

those of their surrounding beds. The salt is hard and homogeneous, and transmits elastic waves with high speed from 16,000 to 18,000 feet per second. The loosely consolidated enclosing beds are slow-speed seismic wave carriers, the velocities ranging normally from 5600 feet per second at the surface to about 10,000 feet per second at 5000 feet depth. Gravimetrically, a shallow salt dome with massive caprock will register as a gravity high or maximum. Deep seated salt masses, that is below 5000 feet, will register as a gravity low or minimum. The enclosing sediments are uniformly denser with depth, above 3000 feet being appreciably less dense than the salt, and below 5000 feet becoming definitely more dense than salt.

The torsion balance measures and records these gravity anomalies. Although invented over thirty years ago by an Austrian physicist, Rould von Eötvös, it was not introduced into the Gulf Coast until late in 1922. The Rycade Oil Company brought over the first instruments, closely followed by Roxana Petroleum Corporation. The Rycade discovery of Nash dome in 1924 is credited as the first geophysical dome discovery on the Coast.[3]

A rapid reconnaissance of the Gulf Coast for maximum gravity anomalies resulted in several dome discoveries. By late 1927, however, the torsion balance was temporarily replaced by the seismograph, a quicker method for locating shallow domes. In late 1928 and early 1929 the discovery of oil at Sugarland and Esperson on gravity minima, however, led to a quick revival of gravimetric exploration and a general re-interpretation of old data. The net result to date for the torsion balance is ten proven salt domes, nine of which are producing or have produced some oil.

The history of the seismograph on the Coast dates from its introduction by Marland Oil Company in 1923, followed closely by Gulf Production and other companies.

The first practical field seismographs were designed in Germany shortly after the World War. Although the principle or

[3] A fuller historical summary of the introduction of geophysical methods into the Gulf Coast is given by D. C. Barton, Applied Geophysical Methods in America, ECON. GEOL., vol. 22, pp. 649–688, 1927.

theory of utilizing artificial shocks for causing seismic waves to determine geologic data was postulated many years ago by various European physicists, it was largely experience gained during the War that led to a practical application of the idea. German scientists were called upon for practical detectors for gun-emplacements, mine sappers and submarines. From the records of these detectors was clearly seen the close relationship between the character of the intervening rocks and the observed seismic velocities.

L. Mintrop, of Hanover, Germany, placed the first serviceable mechanical seismograph on the market. Mintrop instruments were the first that came into the Coast region.

Many independently designed American instruments were developed and placed in the Gulf Coast. Among these inventors are Fessenden, Eckhardt, Karcher, Kannestine, Trueman, McCollum, Petty, E. Rosaire. W. Schweydar, of Berlin, also designed an instrument widely used.

The Gulf Production Company discoveries of Orchard and Longpoint domes by mechanical seismographs in 1924 and early 1925, are the first credited seismic discoveries on the Coast. The success of this Company brought on active competition, and dome discoveries increased annually to 1927, during which year eleven proven domes were found. Twelve were located in 1928, five in 1929, one in 1930, and one in 1931. A total of forty-six accepted domes or oilfields have been credited to the seismograph. A large number of favorable prospects have been delineated.

Vigorous research and a wealth of field experience brought rapid strides in the development of the seismograph and its methods. The early mechanical instruments, capable only of receiving shots from two to four miles, were improved to the point of receiving shots from six to eight miles. Electrical seismographs, permitting unlimited magnifications of the energy received, were developed. By using geophones or electrical receivers on extendable cables, it became possible to work marshlands and water bodies from tractors or boats.

Late in 1926 the Geophysical Research Corporation brought out the reflection type seismograph, the first fundamental innovation

in seismology. Instead of recording the refracted waves at long distances, several detectors are placed close together in profile and record simultaneously the reflected waves. The reflection method is not dissimilar in principle to that of deep sea sonic sounding.

FIG. 3. Mechanical seismograph and camera, showing set-up with tent drawn up to expose instruments. Chapel Hill, Texas, June, 1928.

The reflection method was looked at askance by many for a long time, but its successful application in Oklahoma brought about a justly earned recognition. The prominent sandstones and limestones of Oklahoma proved to be excellent reflectors. In the Gulf Coast the very lack of such markers makes it a less favorable method for reconnaissance. On the other hand good reflections are obtained from the sediments overlying deeply buried salt and caprock. Recognizable reflections have been obtained in experimental investigations within the Gulf Coast from estimated depths of well over 10,000 feet. For the exploration of suspected prospects this method is efficient, reasonable in cost, and time-saving.

Some reflection reconnaissance has been carried out in the Corpus Christi region, and one discovery has been made by this method. Drilling, in 1931, on a structure outlined by reflection work, the Stanolind Oil and Gas Company has developed a potential gas field six miles south of the Agua Dulce field in Nueces County. It is called the Stratton Field.

FIG. 4. Well drilling on dome underlying the waters of Vermilion Bay, Iberia Parish, Louisiana. This dome was accurately located by seismograph and the well location based on this information. The first and discovery well hit the salt of the dome at 810 feet depth, within a few feet of the seismograph predicted depth.

At the present moment, the beginning of 1932, geophysical operations in the Coast are restricted to a limited amount of torsion balance exploration for closed minima and some reflection work. Refraction shooting has been stopped, primarily because of the economic depression and partly because it is generally believed that the field has been covered for domes discoverable by this method.

The depth range of refraction shooting for finding salt domes is approximately 1000 feet of depth for every mile between shot and observation. Thus six-mile shots would probably locate salt at 6000 feet. The deepest known discovery by refractions

on the Coast is the Gueydan dome, Vermilion Parish, Louisiana, where salt was recently found at a depth of just over 6400 feet. This well is probably offside and the highest salt here is estimated to occur at about 5600 feet.

FIG. 5. Explosion of 500 lbs. of dynamite in marsh bordering Vermilion Bay, Vermilion Parish, Louisiana. Similar and larger charges very frequently fired in the Bay itself and as far as six miles off-shore in the Gulf of Mexico.

Geophysicists place the depth range of the torsion balance in mapping salt masses at from 15,000 to 20,000 feet. Obviously these depths are beyond drilling reach and the geophysicist and geologist must look to other methods to confirm the presence of structure in the sediments overlying such deep salt masses.

In addition to closed maxima and minima characteristic of shallow and deepseated domes, the gravimetric exploration of the Coast has revealed a remarkably regular pattern of parallel axes of maxima and minima reversals. These axial lines trend generally northeast-southwest, are from one to several miles apart and range in length from a few to many miles. They are not indefinitely continuous but appear to occur *en echelon*. It is suggested by Barton [4] that the linear minima represent deeply buried salt ridges.

Accepting Barton's hypothesis, the full significance of these salt ridges in the oil geology of the Coast is not yet apparent. At present they are regarded, in oilfield parlance, as "good trends," and unquestionably will bear the brunt of much of the future activity of Coastal geophysical investigations.

The aggregate cost of geophysical prospecting on the Gulf Coast is estimated at thirty million dollars; twenty-six million on seismograph work, three million on torsion balance, and one million on all other methods and experimentation.[5] This geophysical expenditure accounts for about sixty proven structures. In proving and developing these sixty structures some three hundred wells have been drilled at an aggregate cost of fifteen million dollars. Leasing, damage claims and exploration permits, incident to this exploration, have cost five million dollars or better.

Drilling and lease costs should be eliminated for comparative consideration on the basis of being a common factor of expense to any method of exploration or even wildcatting. From the

[4] Barton, Donald C., Petroleum Potentialities of Gulf Coast. Bull. Amer. Assoc. Petrol. Geol., vol. 14, p. 1393, 1930.

[5] These costs were independently estimated by Henry C. Cortes, Vacuum (now Magnolia) Geological and Geophysical Department, and the author; their figures, on comparison, were found in close agreement, and on averaging, become the totals herewith presented.

first geophysical production in 1926, to 1932, approximately thirty-three million barrels of oil have been produced from geo-

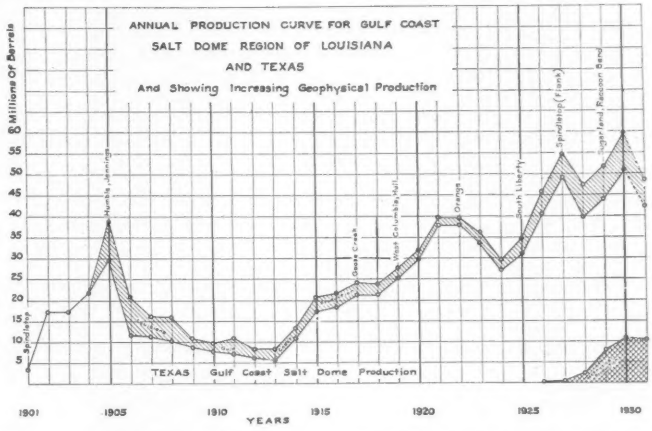

FIG. 6. Annual production curve for Gulf Coast Salt Dome Region of Louisiana, showing also increasing geophysical production.

physically located structures (Fig. 6).[6] At an average valuation of one dollar a barrel, the actual cost of geophysical operations in the Coast has already been returned. In 1930 eighteen and two-tenths per cent. of all Gulf Coast dome production (this excludes Refugio-Kingsville-Pettus area production) was from geophysically located structures. The percentage is nearly twenty for 1931.

Any evaluation of geophysics on the Gulf Coast must recognize the present abnormal situation in the oil business. Normal development has been restricted if not actually suspended. Geophysical domes and prospects are for the most part controlled by individual companies and rarely are subject to the hasty development of competitive drilling. Ten or twenty years from now will

[6] The figures for oil and sulphur production and valuations came largely from Government bulletins, Bull. No. 1, Texas and South Louisiana Oil Scouts Association, and the Oil Weekly through H. J. Struth, Staff Economist.

be time enough to appraise the geophysical discoveries of the last eight years.

It is not wise to attempt to speculate on the ultimate recovery from sixty Gulf Coast domes. Sugarland, Lake Barre, Rabb Ridge and one or two other domes are already clearly major producing fields. Fifty million barrels a dome may be considered a conservative estimate for a producing dome. The geologically located domes, Spindletop, Humble, and West Columbia, have each produced over one hundred million barrels. Should fifty of the geophysical domes produce in accordance with the conservative estimate, an aggregate of two and one-half billion barrels is indicated.

The contribution of geophysics to the sulphur industry is still much of an unknown quantity. The presence of sulphur in caprock can only be revealed by the drill, and where sulphur test drilling has been carried out, the results have been guarded with the utmost secrecy. A number of the newer domes have been drilled by the sulphur companies and rejected, temporarily at least, as not commercially productive. The Long Point dome, Fort Bend County, Texas, is the only geophysical dome to date upon which sulphur is being produced.

When total geophysical costs are integrated according to the years of expenditure and compared to the total annual valuations of the minerals, oil and sulphur, produced, it is seen that geophysical costs average less than five per cent. of the valuation of the minerals produced each year (Fig. 7). Geophysical expenditures have, therefore, been in line with sound business development and, as just pointed out, returning dividends have already approximately equalled the initial geophysical investment. Ten major companies and about ten smaller organizations and a few individuals participated in the general geophysical costs. Obviously enough, not all of those who shared the expense are sharing in the return of production dividends.

The important part that geophysics has played in the outlining and development of the older known domes must not be overlooked. The torsion balance was eminently successful in detail-

ing the structure of Barbers Hill and Boling, leading to new discoveries of oil and sulphur. Every known dome on the coast has in fact been examined one or more times by the seismograph.

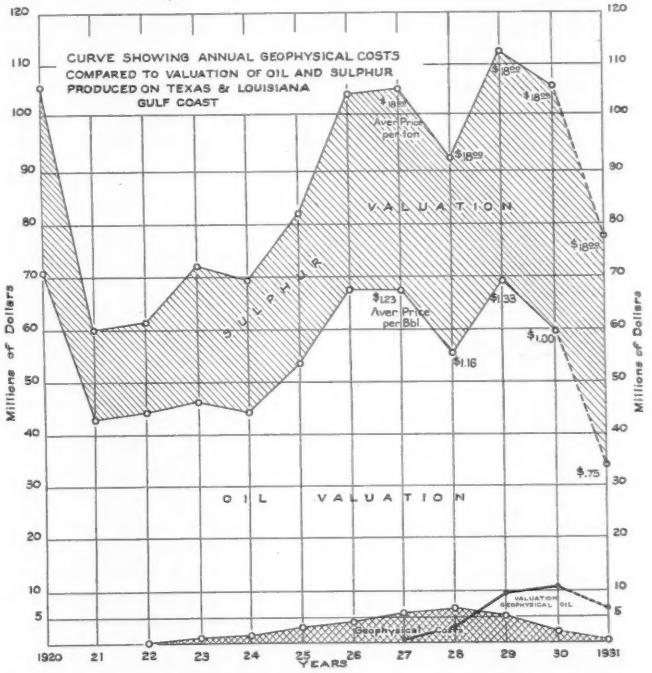

FIG. 7. Curve showing annual geophysical costs compared to valuation of oil and sulphur produced on Texas and Louisiana Gulf Coast.

The future of geophysics on the Gulf Coast will depend largely, as with other forms of exploration, on the current demand for the product sought. Geologically there is ample opportunity for further extensive investigations by both the torsion balance and reflection seismograph.

Drilling on geophysically favored prospects is constantly adding to our ability to interpret geophysical data correctly. The rela-

tionship of geologic structure, formations, and lithology, to observed geophysical effects is gradually being unfolded.

As the science acquires dignity with age, and reputation with success, the barriers of isolated knowledge and effort are progressively lowered. The formation of the Society of Petroleum Geophysicists in Houston in the spring of 1930, marks probably the first step in encouraging the exchange of theories and experience for the general advancement of geophysical knowledge. Geophysics is destined long to remain a dominant factor in the mineral exploration of the Gulf Coast.

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THE ORES OF THE N'CHANGA MINE AND EXTENSIONS, NORTHERN RHODESIA.

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INTRODUCTION.

THIS paper deals with the ores of one of the principal copper deposits of Northern Rhodesia and their enrichment. No attempt is made to give a detailed description of the physical conditions and general geology of the Northern Rhodesian Copper Belt, as this has already been done in other publications.[1]

[1] For details of the petrology and stratigraphy of this portion of Northern Rhodesia, reference should be made to papers by J. A. Bancroft, Anton Gray, and Alan M. Bateman, and for details of the N'Changa District in particular, to a forthcoming paper by the writer, "The Geology of the "N'Changa District, Northern Rhodesia," in the Quarterly Journal of the Geological Society of London. (See, also, bibliography at end of paper.)

The N'Changa deposits, of the Rhokana Corporation, Ltd., lie approximately 12 miles south of the Belgian Congo border, in close proximity to the other principal copper mines of Northern Rhodesia. Mufulira lies approximately 25 miles to the east, while Chambishi, N'Kana, Roan Antelope, and Bwana M'Kubwa lie respectively 14, 30, 50, and 65 miles to the southeast. These deposits are genetically related to one another, and the problems of any one have a direct bearing upon those of the remainder.

The data upon which this paper is based were obtained by the writer during three years of field-work in the N'Changa District on the geological staff of the Rhodesian Congo Border Concession, Ltd., followed by two years of laboratory investigation at the Royal School of Mines, London.

GEOLOGICAL SETTING.

The oldest rocks of the district comprise two great series of ancient arenaceous and argillaceous sediments, regionally metamorphosed, the older of which has been termed the Basement Schist Series, and the younger the Muva Series. These have been invaded by three older granitic intrusives, namely, the M'Kushi Granitic Gneiss, the Muliashi Porphyritic Granitic Gneiss, and the N'Changa Older Red Granite. Overlying unconformably all the foregoing, is the Bwana M'Kubwa Series,[2] consisting of approximately 8,000 feet of argillaceous, arenaceous, and dolomitic sediments, exhibiting low-grade metamorphism. This series has been subdivided into a Lower, Middle, and Upper division, and within the Lower Bwana M'Kubwa Series occur all the great replacement copper deposits of commercial grade now being exploited in Northern Rhodesia. Unlike those of Northern Rhodesia, the neighboring copper deposits of the Katanga, Congo Belge, occur in the dolomitic beds of the overlying Bwana M'Kubwa or Roan Series. Overlying the Bwana M'Kubwa Series with apparent conformity, is the Kundelungu Series, mainly dolomitic and calcareous in character.

[2] Also referred to by other writers as the Roan Series. See also correlation with "Series des Mines," by Anton Gray, ECON. GEOL., Vol. 25, pp. 783–804, 1930.

Intrusive into all the above are stocks and batholiths of the Younger Gray "Granites" and the N'Changa Younger Red Granite, together with sills of gabbro and norite of the Basic Intrusive Group showing varying degrees of auto-scapolitization.

THE GEOLOGY OF THE N'CHANGA MINERALIZED AREA.

The generalized geology of the N'Changa mineralized area is shown in Fig. 1, and details of the geology of the original N'Changa Copper Mines, Ltd., Concession, in Fig. 2.

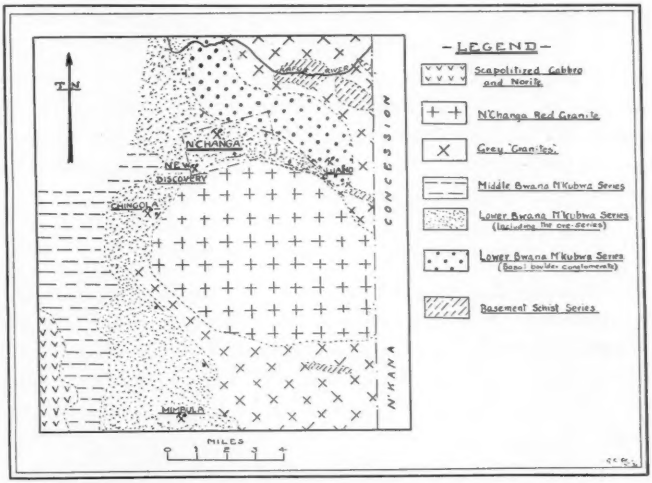


FIG. 1. Sketch map showing the generalized geology of the N'Changa mineralized area, and the relative position of the several copper deposits.

The deposits of the N'Changa Area, now forming part of the holdings of the Rhokana Corporation, Ltd., comprise N'Changa, New Discovery, N'Changa West Extension, Chingola, Mimbula, and Luano. Of these, the first three are of principal economic importance.

These copper deposits occur exclusively in beds of the Lower Bwana M'Kubwa Series, and all, with the exception of that of

Mimbula, lie within the N'Changa syncline; Mimbula lying on a southward extension of its southern limb. This syncline, surrounding the northern margin of the N'Changa Red Granite stock, lies with its apex at Luano, two miles to the east of N'Changa, and plunges gently westward, passing successively beneath N'Changa, New Discovery, N'Changa West Extension, and Chingola: the last named lying about four miles to the southwest of N'Changa. The syncline at Luano is strongly overturned to the south and is tightly compressed. At N'Changa, the northern or River Lode limb is slightly overturned, although nearly vertical; the southern or Dambo limb dips approximately 30° to the north; the mineralized horizons on either side of the syncline are, at this point, approximately 4,500 feet apart. At Chingola, the syncline widens abruptly, the northern limb bends north and crosses the Kafue River near the Kafue Falls, and the southern limb turns southward and subsequently eastward, around the Red Granite stock, eventually reaching Mimbula.

DESCRIPTION OF THE PRINCIPAL DEPOSITS.

N'Changa Mine and Extensions. The N'Changa Mine and its associated ore bodies together constitute one of the principal mineralized centers of Northern Rhodesia. Copper occurs in the Lower Bwana M'Kubwa rocks on both limbs of the N'Changa syncline (Fig. 2). The group carries a large tonnage of relatively high-grade ore.

The N'Changa mineralized zone includes the following separate ore bodies:

The River Lode on the north limb of the syncline; the Dambo Lode directly opposite on the south limb; New Discovery westward along the strike from the Dambo Lode, but within the original N'Changa Copper Mines, Ltd., Concession; N'Changa West Extension, still farther westward along the strike of the southern limb from New Discovery, *i.e.* between New Discovery and Chingola.

The official tonnage of ore within the N. C. M. Concession, proved up to March, 1931, has been stated at 64,641,000 tons

FIG. 2. Geological Plan of N'Changa Copper Mines, Ltd., Concession, with section through Dambo and River Lodes.

averaging 3.78 per cent. total copper. This figure represents the total of three separate lodes, as follows:

River Lode: 2,278,000 tons assaying 4.21 per cent. total copper, of which 2.92 per cent. is in the form of sulphides.

Dambo Lode: 8,193,000 tons assaying 3.74 per cent. total copper, of which more than half is in the form of sulphides.

New Discovery: 54,170,000 tons assaying 3.77 per cent. total copper, of which 1.32 per cent. is in the form of sulphides.

In addition to the above tonnages, the proved ore of N'Changa West Extension consists of 30,000,000 tons averaging 6.6 per cent. total copper.

Thus the total reserves of the above lodes includes nearly one hundred million tons of commercial ore.

In view of the nature of the ore bodies, and the method of computation, it may be assumed that these figures are conservative; the probable tonnage is considerably greater.

TABLE I.

TABLE OF FORMATIONS, N'CHANGA MINE.

Series	Formation	Thickness (feet)
Middle Bwana M'Kubwa..	Dolomites and dolomitic schists with arenaceous and argillaceous facies	1000
Lower Bwana M'Kubwa ..	Cherts—silicified dolomite	15
	Dolomite and dolomitic schist	220+
	Upper Banded (phyllitic) Shales	75
	Feldspathic quartzite, arenaceous schist, and phyllitic shales, interbedded	40
	Feldspathic quartzite	65
	Feldspathic quartzites, arenaceous schists and phyllites, interbedded	100
	Lower Banded (phyllitic) Shales	70
	Arkosic schists, (biotite) schist and conglomerate interbeds on part of north limb of syncline	100
	Footwall (quartzitic) arkose	300
	Orange Schistose Grits, abundant conglomeratic interbeds	2000
	Sheared boulder conglomerate	3000
	GREAT UNCONFORMITY	
Basement Schists	Kafue Chlorite Schists	Very great

The stratigraphical succession of the rocks of the Lower and Middle Bwana M'Kubwa Series is given below. This succession is that observed in the vicinity of the original River Lode and Dambo Lode workings. The thicknesses of the component formations vary considerably from place to place, those given below representing the average. Petrographic details of these formations are given in the writer's forthcoming paper referred to in footnote 1.

Faulting appears to be present only on a minor scale. Small transverse faults were noted in the shallower levels of the original River Lode workings. Probably, as underground development proceeds, other faults will be encountered. It seems that the beds have yielded to stresses by folding rather than by fracturing, and it is unlikely that large-scale faulting will ever become a serious consideration in mining at N'Changa.

Folding is common and has evidently played an important part in the localization of the richer portions of the Lodes. Drag-folds occur abundantly on the limbs of the main N'Changa syncline, and along the axes of these minor folds occur many of the principal deposits such as the rich ore body at New Discovery.

The bending and fracturing of otherwise impermeable beds along the axes of these minor folds rendered them specially favorable to entry by mineralizing solutions, both hypogene and supergene. This is indicated also on a larger scale by the N'Changa syncline as a whole, which probably owes much of its mineralization to its position as a relatively tightly-compressed fold, caught up between two competent granitic masses, either or both of which may have been responsible for the primary mineralization.

Chingola Prospect. Chingola lies on the southern limb of the N'Changa syncline, approximately three and a half miles southwest of the N'Changa Mine.

Copper mineralization was first noted several years ago, as malachite-stained outcrops of chert near Chingola Stream. This chert, which occurs in the dolomite at the top of the Lower Bwana M'Kubwa Series, was proved by development to be too poorly

mineralized to constitute commercial ore. Recent drilling has proved a moderate sized ore body of good tenor in a large subsidiary syncline to the south of the discovery outcrop. This deposit is of special interest because much of it occurs at a sufficiently shallow depth to permit of open-cast mining. Ore occurs on both the Upper and Lower horizons, but is found mainly on the Lower.

The Chingola ore body forms the most westerly of the mineralized zones of the N'Changa syncline. This syncline at Chingola extends to considerable depths, and is rather complexly folded and overturned near its axis to the north of the present ore body. This intensity of folding over the central portion of the syncline at Chingola may possibly have resulted in the deposition of an ore body of commercial grade, similar to the rich deposit at New Discovery, which occurs over an area of folding much less intense than that of Chingola. Drilling has not yet been carried to sufficient depths to reach the ore horizons of the central portion of the Chingola syncline, and the problem is further complicated by strong overturning of much of the series.

Luano Prospect. This prospect, at the eastern extremity of the N'Changa syncline, is underlain by the Lower Banded Shales and older formations of the Bwana M'Kubwa Series, the whole being strongly overturned to the south.

Mineralization consists principally of chalcopyrite and bornite in the shale and arkose, and is associated with a zone of strong silicification. This silicification has rendered the beds highly impermeable, with the result that the sulphide ore is found practically at the outcrop, an unusual feature in Northern Rhodesia. The mineralization is apparently too low-grade to be economic.

A feature of geological interest is the presence of several small hot-springs in the dambo bordering the Luano Stream. These springs occur along the zone of silification and mineralization referred to above, and were sufficiently active to have caused one of the earlier prospecting pot-holes to be abandoned owing to flooding by hot water.

Subsequently, a large diameter shot-drill hole, put down in the

dambo to cut the lode at depth, penetrated five fissures carrying hot water. This interception caused the several hot-springs of the dambo to become dry, and the entire flow to emerge permanently and with considerable force from the collar of the drill-hole.

The temperature of the water is approximately 80° C. Barite crystals were noted in one of the fissures penetrated by the drill, and the water gives a weak sulphate reaction.

Whether these springs are of juvenile or meteoric origin is uncertain. Their association, however, with the zone of mineralization is significant; they may possibly owe their origin to a late and dying stage of vulcanicity.

Mimbula Prospect.[3] Mimbula lies eight miles south of N'Changa, from which it is separated by the N'Changa Red Granite stock. It is underlain by rocks of both the Basement Schist and the Muva Series, in which are infolded remnants of the Lower Bwana M'Kubwa, up to a horizon slightly above that of the Lower Banded Shales. This complex has been much folded and portions of it are overturned. This infolded remnant of the Bwana M'Kubwa Series forms an extension of the southern limb of the N'Changa syncline, which recent detailed work has shown to extend southward from Chingola, around the western margin of the Red Granite stock into Mimbula.

Copper mineralization is confined to the rocks of the Bwana M'Kubwa Series, which here consist of arkose, conglomeratic schistose grits, and phyllitic shales; the last named being calcareous at depth.

Ore of commercial grade has been proved by both trenching and drilling, but owing to the complexity of folding there has been considerable difficulty in following the lodes. Data from the earlier drill-holes indicated that copper mineralization is confined to the more calcareous beds.

[3] The writer is greatly indebted to Dr. L. E. Reber, and Mr. H. G. Hymer for data concerning the original mapping of Mimbula during the field work of 1926 and 1927; and to Dr. D. H. Ellis for a concise outline of the recent field data.

N'CHANGA MINE AND WEST EXTENSION.

Nature of the Ore Bodies.

The ore bodies of N'Changa, like those of the other important copper deposits of Northern Rhodesia, are composed of lenticular beds of partially replaced sediments to which they conform in strike and dip. These mineralized sediments consist of schists, phyllitic and hornfelsic shales, and feldspathic quartzites overlying the basal arkosic beds of the Lower Bwana M'Kubwa Series; they all occur within a narrow stratigraphical limit of approximately 400 feet.

The ore at depth consists of finely disseminated chalcopyrite, bornite, and chalcocite; chalcocite being, in general, the most abundant. Rarely, the sulphide particles occur in rounded clusters throughout the rock, up to one-quarter inch in diameter. This cluster type is typical of the sulphide ore in the Feldspathic Quartzite. The deposits owe the greater part of their copper content to enrichment by chalcocite and bornite; chalcopyrite being the primary copper ore-mineral.

Oxidation of the sulphides is usually nearly complete from the surface to depths of two or three hundred feet; the upper one hundred feet being, in addition, usually thoroughly leached. Below the zone of oxidation, the zone of sulphide enrichment continues to depths in excess of 2000 feet.

In many of the deposits the metamorphosed sediments of the ore-series vary greatly in permeability, the more porous beds being oxidized to considerably greater depths than those which are less porous. At such localities the lode may contain at any one level, alternate bands of sulphide and oxide copper minerals. This co-existence will constitute one of the chief mining and metallurgical difficulties of the district.

Distribution of the Ore Bodies.

At the original workings of the N'Changa Mine, ore was found at different horizons on either side of the syncline. On the northern, nearly vertical, River Lode limb, the ore occurs principally in the Lower Banded Shales and associated beds, whereas on the

southern, gently dipping, Dambo Lode limb, it occurs at a higher horizon, principally within the Feldspathic Quartzites and associated beds. Mineralization had not at that time been found at both of these horizons, on the same limb.

More recent development, however, on the southern limb of the syncline between N'Changa and Chingola, has proved the existence of high-grade and large deposits on both horizons. Mineralization of the Upper Horizon has in part of this area overlapped, in plan, that of the Lower Horizon (Fig. 3), and several vertical drill-holes in this area have cut both these horizons.

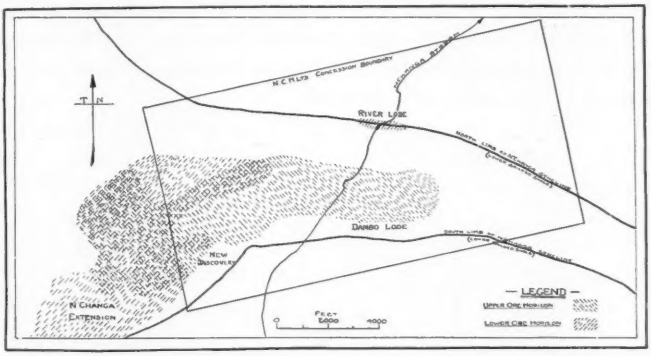


FIG. 3. Sketch plan showing overlap of Upper and Lower mineralized horizons.

It is not clear why, in one part of the N'Changa syncline, certain horizons should have been mineralized in preference to others that have been mineralized elsewhere. Possibly the Lower Banded Shale normally acted as an impermeable barrier to rising hydrothermal solutions, except where locally dislocated to allow these solutions to rise to still higher stratigraphical horizons until they were checked near the base of the relatively impermeable Upper Banded Shale. It may be that at some point on the southern limb of the syncline, the Red Granite broke through the impermeable Lower Banded Shale and admitted mineralizing solutions directly into the beds of the Upper Ore Horizon. A point

of interest in this connection is the fact that close to the outcrop of the Red Granite, *e.g.* at the Inclined Shaft workings, the ore is in the Upper Horizon; whereas farther from the granite, *e.g.* at the River Lode workings, ore occurs only in the Lower Horizon.

By some such mechanism, and from feeders probably occurring at a considerable distance apart, the two separate lodes on the southern limb at N'Changa may have been formed. By lateral spread from these feeders, overlap of the lodes would take place.

Mineralogy and Paragenesis.

The generalized paragenesis of mineralization of the N'Changa ore bodies, determined by field and microscopical study, is as follows, commencing with the oldest:

Primary	Pyrite
	Chalcopyrite
	Linnaeite (and carrollite?)
	White mica and colorless chlorite
	Microcline
	Quartz
	Calcite and dolomite
Secondary	Bornite (and chalcocite)
	Chalcocite
	Cuprite
	Native copper
	Malachite, azurite, and bieberite
	Chrysocolla
	Limonite

The occurrence of these minerals and the evidence for this succession are discussed in detail in the following pages:

Gangue Minerals. The principal gangue minerals are those of the country rocks through which the copper ore-minerals are disseminated. There are in addition very subsidiary amounts of quartz, white mica, colorless chlorite, calcite and dolomite, all of

hydrothermal origin, which accompanied, but crystallized slightly later than, the primary sulphides.

Pyrite. The copper field of Northern Rhodesia is conspicuously poor in iron and sulphur. This is reflected in the comparative scarcity of pyrite.

At N'Changa, this mineral appears to be primary in all observed occurrences. It has been noted in microscopic quantities on the 300-foot level of the River Lode workings, where it occurs in association with chalcopyrite. Pyrite is more typically developed, however, as a marginal phase of the copper mineralization in the Lower Ore-Horizon of the south limb of the N'Changa syncline, particularly in the New Discovery area.

Where the enclosing beds have been sufficiently permeable, pyrite has been replaced by supergene chalcocite. This replacement, however, seems to be rather uncommon, probably owing to the fact that pyrite mineralization was accompanied by much silicification of the host-rocks, rendering them unusually impervious to meteoric waters.

A noteworthy phase of pyrite mineralization was observed in a drill-core obtained from a hole penetrating the pyritic margin of the ore body (N.E. 13 at 1633 ft.). A siliceous hornfels at the base of the Lower Banded Shale showed distinct spotting, the spots being composed of clusters of minute pyrite granules. The microscope showed clear evidence of the introduction of silica followed by iron sulphide, under conditions of low-grade contact metamorphism, resulting in hornfelsing of the rock, and segregation of pyrite into spots about definite foci.

Chalcopyrite. This is the primary copper mineral of the deposits. It occurs sparingly, however, and is in general found only at depth, or when nearer the surface, in the more silicified beds. In all cases, so far as the writer has observed, the chalcopyrite is partially replaced by bornite or chalcocite, or by both. The various relationships of chalcopyrite, bornite, and chalcocite to one another are discussed in detail in a later section.

Chalcopyrite occurs mainly in the more siliceous of the phyllitic shale horizons, usually in those of the Lower Ore Horizon. It

is uncommon in the feldspathic quartzites of the Upper Ore Horizon, except where they contain the cobalt sulphides, linnaeite and carrollite. The normal sulphide copper ore of the feldspathic quartzite consists of bornite and chalcocite, occasionally showing on polished surfaces microscopic cores of unreplaced chalcopyrite; it is not apparent why chalcopyrite should be abundant only where it is associated with primary cobalt sulphides.

Chalcopyrite mineralization appears to have been accompanied by strong silicification, the sulphide grains commonly showing, in thin section, a shell of introduced quartz. The mineral also occurs as masses and segregations in narrow veins of glassy quartz cutting the ore bodies.

Linnaeite. Linnaeite is found in small quantities in many drill-cores of the N'Changa mineralized area. In two holes (D–15 and B–21), however, it occurs abundantly; assays from drill-hole D–15 show more than 2 per cent. each of both cobalt and copper.

In all specimens examined, linnaeite occurs exclusively in the more arkosic beds; chiefly in the Feldspathic Quartzites, and to a lesser extent, in the Footwall Arkoses. It is a primary mineral, and is commonly intergrown with chalcopyrite. Partial replacement by chalcocite and bornite was noted in all specimens. Details of this replacement, which shows several features of interest, are given in the section headed "Replacement of Linnaeite by supergene chalcocite."

The identity of linnaeite has been carefully checked, both physically and micro-chemically, against the type linnaeite of Musen, Prussia, with which it appears to be identical.[4] Like the linnaeite of the Katanga, however, it is nearly nickel-free.[5]

The comparative age of the linnaeite and chalcopyrite of the N'Changa deposits is doubtful, practically every specimen examined showing mutual intergrowths between the two minerals.

[4] The writer is greatly indebted to Dr. L. J. Spencer, F. R. S., for the loan of several specimens of the Prussian linnaeite, from the collections in the Mineralogical Section, British Museum, South Kensington.

[5] Spectroscopical examination by Dr. C. S. Hitchen of specimens of the N'Changa linnaeite furnished by the writer, showed, in all cases, appreciable quantities of nickel.

One specimen was noted, however, in which linnaeite, inclosed in and inclosing chalcopyrite, showed crystal outlines suggestive of parallel growth of idiomorphic crystals. This would appear to indicate that the linnaeite is slightly later in age than the chalcopyrite, at the expense of which it grew (Fig. 4).

Why the linnaeite should favor the more coarsely feldspathic beds is not clear.

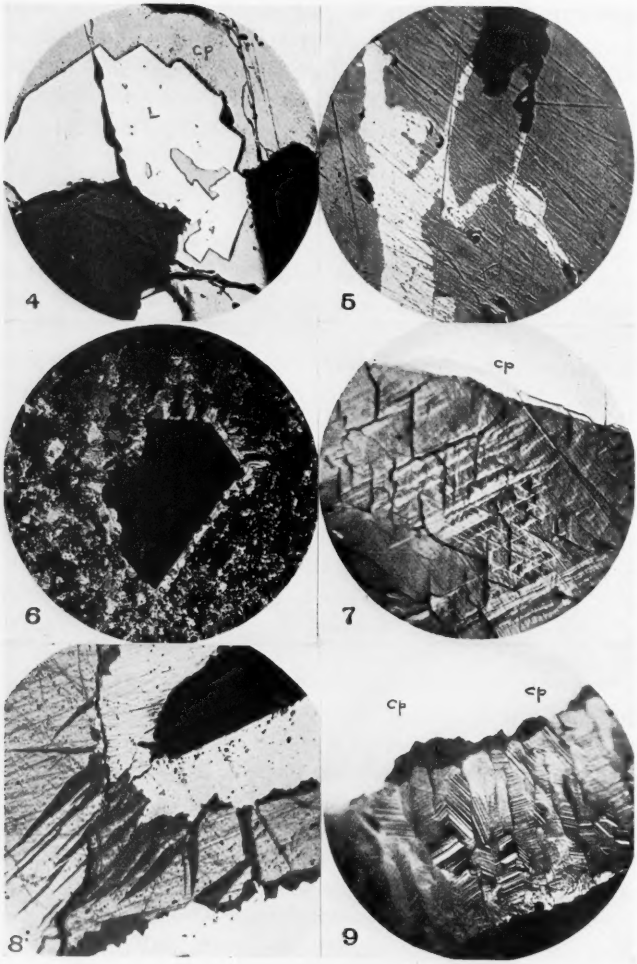
Carrollite (?). A mineral, doubtfully referred to carrollite, has been observed in the core of one drill-hole, in minute quantities intergrown with linnaeite. This mineral is a cobalt sulphide, containing some copper, but evidently having a lower cobalt content than linnaeite. It occurs too finely intergrown, and in insufficient quantities, to enable a separation to be made for accurate chemical analysis. The presence of chalcopyrite in the same specimen suggests the possibility of carrollite, or of some cupriferous linnaeite.

Bornite. With the doubtful exception of certain rare occurrences in graphic intergrowth with chalcocite, all the bornite of the N'Changa deposits appears to have been formed by the supergene replacement of chalcopyrite. Bornite at N'Changa is an important sulphide mineral, ranking second in abundance to chalcocite. It occurs mainly in the deeper zones of sulphide enrichment, where it forms an intermediate stage between chalcopyrite and chalcocite.[6]

Chalcocite. This is the most abundant sulphide copper ore-mineral of the N'Changa deposits. With the possible exception of very subordinate amounts forming graphic intergrowths with bornite, all the chalcocite is supergene. It has formed as a product of the replacement and enrichment of primary chalcopyrite, and to a much lesser extent, primary pyrite and linnaeite. In by far the greater number of specimens, chalcocite "rims" the older sulphides, bornite and chalcopyrite. The relationship of chalcocite to bornite and chalcopyrite is discussed in detail later.

Cuprite. Cuprite—somewhat rare in the original N'Changa ore body—is an important ore mineral in the New Discovery area.

[6] Bancroft, J. A., personal communication to the writer.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Although it is a mineral of the oxidized zone, it occurs, like malachite, in the permeable beds of some of the deepest holes, *e.g.* at depths of over 1600 feet.

Detailed microscopic study of the cuprite shows it to have originated as an immediate oxidation product of chalcocite, there being no intermediate stage in its development.

Examination of polished sections under high magnifications indicates that cuprite replaces chalcocite along reticulating veinlets and margins, the resulting pattern being similar to that produced by the replacement of chalcopyrite or bornite by chalcocite. Malachite, or a granular mixture of malachite and limonite, sometimes occurs as a micro-selvage between the cuprite and the chalcocite, and is evidently the result of further oxidation and replacement along contacts, being clearly later than the replacement of chalcocite by cuprite.

Native Copper. Native Copper is subordinate in the River Lode workings on the 300-foot level; it occurs rather more abundantly in drill-cores from the New Discovery area on the Dambo Limb of the syncline, in the oxidized beds down to depths of over

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FIG. 4. Linnaeite (*l*) surrounded by and enclosing chalcopyrite (*cp.*). Black is gangue. Upper Ore Horizon, Drill-hole B–21 at 996 ft. × 62.

FIG. 5. Native copper (light gray) replacing chalcocite (dark gray). Black is gangue. Lower Banded Shale, 300 ft. level, River Lode workings. × 350.

FIG. 6. Crystal of pyrite (black) surrounded by corona of microcline and quartz. Upper Ore Horizon, Drill-hole D–17. Crossed nicols, × 20.

FIG. 7. Portion of chalcocite "rim," showing chalcocpyrite (*cp*) replaced marginally by chalcocite (dark gray) containing blade-like segregations of bornite (light gray). Etched surface. Lower Ore Horizon, Drill-hole N.E. 21 at 579 ft. × 445.

FIG. 8. Chalcopyrite (medium gray) replaced marginally by chalcocite (light gray), with segregations and blades of bornite (dark gray) at contact. Black is gangue. Lower Ore Horizon, 300 ft. level, River Lode workings. × 45.

FIG. 9. Chalcopyrite (*cp*) replaced by marginal rim of chalcocite (lamellar structure), with selvage of bornite (*b*). Black is gangue. Note the mosaic of blue and white lamellar chalcocite, typical of etched surfaces of "rim" chalcocite at N'Changa. Lower Ore Horizon, 300 ft level, River Lode workings. × 445.

1600 feet. It is definitely a secondary mineral and occurs only in small masses; the individuals seldom exceed one centimeter in length, and more commonly they are of microscopic dimensions.

In the River Lode workings, native copper is found as small masses and veinlets directly replacing chalcocite (Fig. 5).

The native copper of the New Discovery area occurs as small aggregations or delicate clusters in vugs in the arkose. More commonly, however, it is found in microscopic dimensions within the cuprite, and has evidently been formed from that mineral.

Apparently the native copper is confined to the Lower or River Lode Horizon exclusively, and does not involve the Upper or Dambo Horizon.

Malachite. This mineral occurs as fine disseminations in the oxidized beds, and as superficial oxidation shells and veinlets associated with sulphide copper and cuprite particles. In the rich malachite ore of the Feldspathic Quartzite, it forms a reticulating system of veinlets surrounding and connecting grain surfaces of the clastic components of the rock. It never, however, occurs in great quantities comparable to those of the Katanga deposits.

Malachite occurs at N'Changa at all depths from the surface to the deepest points attained by drilling, namely, over 1600 feet below the surface. Like the other oxidized minerals of the deposits, its formation depends not so much upon depth beneath the surface as upon the permeability of the particular bed in which it occurs. It replaces chalcopyrite, bornite, chalcocite, and cuprite.

Azurite. This mineral is rare at N'Changa. It has been found, however, in nodular masses up to 6 inches in length in the feldspathic quartzite of No. 2 Inclined Shaft, Dambo Lode, where meteoric waters were trapped by veins of quartz.

It has been noted also as small particles in the carbonate ore of New Discovery on the Lower Ore Horizon, at depths of over 1400 feet, where it is intergrown in simultaneous crystallization with malachite.

Bieberite. Bieberite has been noted in, and immediately beneath, the linnaeite-bearing Feldspathic Quartzite from drill-hole D–15 of the Dambo Lode. It occurs sparingly as rose-red crusts at first sight suggesting erythrite, and has resulted from recrystal-

lization of cobalt sulphate solutions liberated during replacement of linnaeite by chalcocite or covellite.

This mineral is rare in Central Africa. It was first noted in Southern Rhodesia in 1926, at the Copper King Mine, Lomagundi District.[7]

Chrysocolla. This mineral occurs in subordinate amounts in the oxidized portions of the deposit. It is pale blue-green, becoming, by hydration, opaque china-blue. The Rhodesian chrysocolla is typically low in copper, which often serves as little more than a pigment to the silica gel. The birefringence is low (0.010); this may possibly be due to the low copper content, the mineral in composition and optical properties approximating to amorphous silica.

At N'Changa chrysocolla appears to be later than, and to replace, malachite, and commonly exhibits a microspheroidal structure under crossed nicols. This order of deposition is the reverse of that at some other localities; *e.g.* at Globe, Arizona, the chrysocolla is reported to be older than malachite.

Limonite. Limonite[8] is common in small quantities in all oxidized portions of the lodes, and appears to be the latest mineral to form. It occurs at the outcrop of the lode in the form of pseudomorphs after chalcopyrite and chalcocite, and commonly shows a tendency to boxwork structures. This feature is well developed in the mineralized feldspathic quartzites, which are sufficiently rigid to preserve these structures against oxidation slumping.

Limonite replaces both malachite and chrysocolla, commonly growing at the expense of these minerals in delicate arborescent forms. In detail, this arborescent structure is made up of an aggregate of spheroidal particles showing zonal growth.

Primary Mineralization.

Origin. In the writer's opinion, the primary mineralization at N'Changa and its extensions consists of chalcopyrite with sub-

[7] Geol. Surv. of Southern Rhodesia, Report of the Director for 1926, p. 9.

[8] The term limonite is here used in a general sense and implies any mineral ferric hydrate.

ordinate amounts of pyrite and the cobalt sulphides, linnaeite and carrollite. These minerals occur in small quantities as compared with the secondary supergene sulphides, bornite and chalcocite, and alone would never have given rise to ore.

There is abundant evidence, both field and microscopical, to indicate that the primary sulphides of N'Changa are related to the hydrothermal phase of a granitic intrusion, and are not of a syngenetic sedimentary origin. A summary of this evidence is submitted below.

Field evidence will be considered first. Primary chalcopyrite has been found in the N'Changa Younger Red Granite at Luano, associated with aplites and pegmatites. At N'Changa Mine, an open-cut in the same granite discloses small fissures filled with chalcopyrite in a fluorite gangue—clear evidence of the association of chalcopyrite with paulopost magmatic phenomena. In the New Discovery area, near a large drag-fold carrying some of the richest ore, the Younger Red Granite is strongly mineralized with malachite, which has the appearance of being due to oxidation of primary copper sulphides in place. Small veins of quartz and dikes of red microcline pegmatite cutting the ore-beds commonly contain segregations of chalcopyrite.

Microscopical evidence lends further support to the magmatic source of these sulphides. Chalcopyrite and linnaeite are commonly surrounded and penetrated by sprays of colorless chlorite and, rarely, white mica. Pyrite granules are commonly inclosed in a micro-shell of siliceous or pegmatitic material. Such a condition is illustrated in Fig. 6, showing a crystal of pyrite within a narrow aureole composed of clear microcline, and a little quartz. This aureole represents pegmatitic juices accompanying the sulphide, which, upon crystallization of the latter, were rejected towards the margins. The whole rock is likewise seen to be saturated with this pegmatitic material. Nearly every granule of chalcopyrite or pyrite examined in thin section is seen to be accompanied by an abundance of introduced silica in the form of quartz. It is noticeable that none of the granules of bornite or chalcocite of N'Changa have, so far as the writer has observed,

displayed any such hydrothermal associations, thus again emphasizing their supergene origin.

From the field evidence submitted above, it may be inferred that the intrusive responsible for the primary sulphide mineralization at N'Changa is probably the N'Changa Younger Red Granite. It is possible, however, that part of the mineralization may be referable to the Younger Gray "Granite," large stocks of which occur in the Kafue Valley, less than two miles from the River Lode workings, and which may underlie the N'Changa syncline at no great depth. The Younger Gray "Granite" appears to have been responsible for the copper mineralization in the case of most of the other Northern Rhodesian deposits.

By analogy with the Kupferschiefer of the Mansfeld area of Central Germany, the suggestion has from time to time been put forward that these Rhodesian ores are syngenetic in origin, *i.e.* contemporaneous with the enclosing rocks. A consideration of the facts recorded above will indicate that a syngenetic origin is highly improbable. Although the Bwana M'Kubwa sediments are continuous in strike for distances of over a hundred miles, the mineralized portions constitute only a fraction of the total extent of the series. Further, the lodes are, in general, confined to areas adjacent to granitic intrusives, and are commonly richest in the more highly folded beds.

Age. The primary mineralization appears to have followed the later stages of folding and regional metamorphism of the Bwana M'Kubwa Series, and to have accompanied fracturing resulting from the intrusion of the Younger Granitic rocks, both Red and Gray.

In the more closely folded portions of the syncline, as in the phyllitic Lower Banded Shales of the N'Changa River Lode, chalcopyrite has been deposited along certain favorable bedding laminae, but the individual sulphide particles have filled microfractures parallel to the planes of schistosity, transverse to the bedding. That these microstructures do not represent post-mineralization distortion of a micro-augen character has been determined from a study of sections cut parallel to the planes of

schistosity, the sulphide masses being roughly equidimensional and showing, in those planes, no elongation parallel to any particular stress direction.

Again, the association of chalcopyrite with quartz veins suggests that mineralization, (and the formation of these veins) took place after regional metamorphism had practically ceased, but while the rocks were subjected to transverse fractures and strain during the intrusion of the granites.

Association with quartz and pegmatite veins. Small veins of quartz and red pegmatite are commonly met with in the underground workings. These veins, averaging a few inches in thickness, traverse the ore beds and may carry small segregations of copper sulphides consisting mainly of chalcocite and bornite. The presence of massive bornite and chalcocite within these veins has at times been put forward as an argument in favor of the primary origin of these two copper minerals. Close study under the microscope of a number of polished sections of such specimens has clearly indicated, however, that the larger masses of chalcocite contain a core of bornite which they have rimmed and veined with a structure typical of supergene replacement. Similarly, though less commonly, residual cores of chalcopyrite have been observed within both bornite and chalcocite. In the writer's opinion, the evidence is very strong that these veins brought in only one primary copper mineral, namely chalcopyrite. Subsequently, meteoric waters attacked and replaced the chalcopyrite, depositing supergene bornite and chalcocite.

Secondary Enrichment.

The Chalcopyrite-Bornite-Chalcocite Relations. As previously mentioned, the primary copper ore-mineral of the N'Changa deposits is chalcopyrite. Subsequent replacement by meteoric waters has led to enrichment by supergene bornite and chalcocite. In this section it is proposed to discuss some of the features of this replacement.

Chalcocite is by far the most abundant sulphide ore-mineral of the N'Changa deposits; bornite is next in abundance to chalcocite

but occurs in much smaller quantities; chalcopyrite is relatively uncommon, having been largely replaced by both bornite and chalcocite.

Of the various forms of supergene replacement at N'Changa, that exhibiting rim-structure is the most common; probably nine out of every ten specimens containing chalcocite show this structure. In certain of the deposits of the N'Kana Concession[9] the reverse is the case, supergene rim-structures being comparatively scarce.

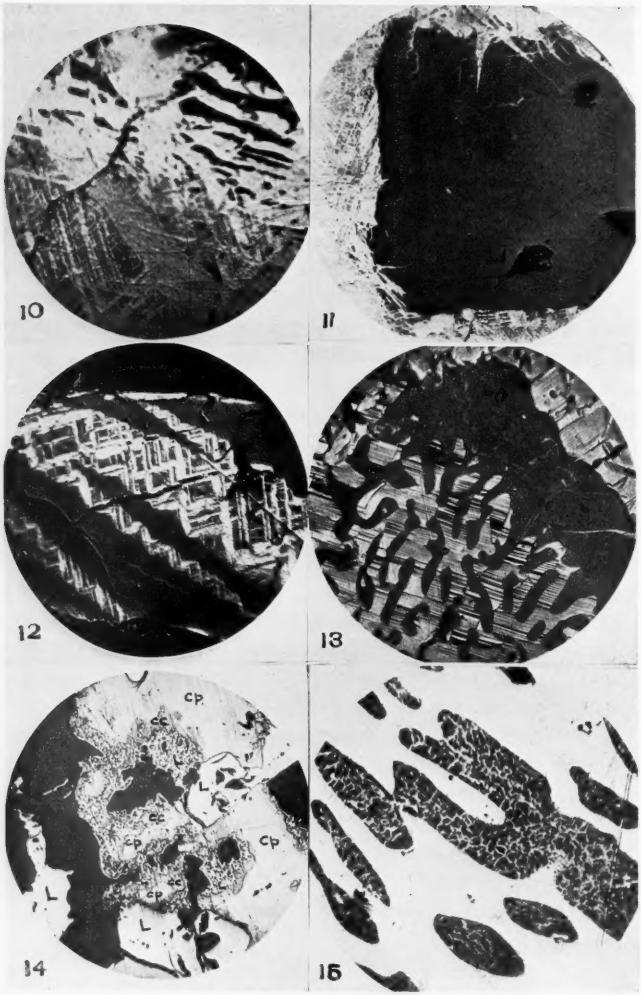
The most common combination is chalcocite rimming bornite or chalcopyrite. The core of the host mineral is commonly penetrated by blades and veinlets of the guest mineral which rims it, and presents a ragged appearance.

Rim structure is a definite indication of replacement. That such replacement is supergene is generally admitted; there is little doubt that this is the case at N' Changa.

Rarely, chalcocite appears to replace chalcopyrite directly, but even in these cases careful examination of etched surfaces under high magnifications (1,000 to 2,000 diameters) usually reveals bornite as an intermediate phase. This bornite generally occurs just within the chalcocite rim, and rapidly diminishes in quantity away from the chalcopyrite margin (Fig. 7). The photomicrograph was taken at the immediate contact of a wide rim of supergene chalcocite replacing chalcopyrite. Only a small portion of this wide chalcocite rim is shown in the field, and it was noted that the blades of bornite segregating out within this obviously supergene chalcocite diminished rapidly in quantity at all points away from the immediate contact of the chalcocite with the bornite. This bornite is evidently supergene and represents a transition phase of diminishing iron and sulphur. Commonly, bornite occurs as a marginal selvage between rim chalcocite and chalcopyrite, often penetrating the chalcopyrite as minute blades and veinlets (Fig. 8).

Etching produces a characteristic pattern in the N'Changa chalcocite of rim habit. Under this treatment the chalcocite

[9] Bateman, A. M.: The Ores of the Northern Rhodesia Copper Belt. ECON. GEOL., vol. 25, p. 401, 1930.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breaks down into a fine granular mosaic, each individual of the mosaic averaging approximately 0.02 mm. in its longest dimension and commonly exhibiting a marked lamellar structure resulting from the alternation of blue and white chalcocite (Fig. 9). The individuals of this mosaic are elongated roughly parallel to the chalcocite-chalcopyrite contact, to which the lamellae tend to be parallel. This development of a micro-mosaic showing lamellar structure is believed by the writer to be diagnostic of the definitely supergene chalcocite at N'Changa (cf. the chalcocite of "graphic" intergrowth described in a later section). Lindgren[10] refers to one form of mosaic structure, as follows:

"The distinctly supergene chalcocite develops by peripheral replacement or along reticulating cracks . . . and etching shows it to have always a granular texture, each grain being striated in one direction, probably that of (001)."

Much of the N'Changa chalcocite shows, upon etching with nitric acid, the well known "cracked porcelain" structure, in place of the lamellar structure described above. This structure

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FIG. 10. Bornite (dark gray) replaced marginally by rim of chalcocite (light gray), with lattice structure controlled by bornite cleavage. Upper Ore Horizon. Drill-hole D–12 at 804 ft., Dambo Lode. × 800.

FIG. 11. Same specimen as Fig. 10 under lower magnification, showing marginal rim of chalcocite. × 44.

FIG. 12. Bornite (dark gray) replaced by chalcocite (light gray), in "plaid" pattern. Black is gangue. The elongation of pattern is parallel to the fracture-cleavage of the surrounding rocks. Lower Ore Horizon, 300 ft. level, River Lode workings. × 305.

FIG. 13. Etched surface of intergrowth between bornite and chalcocite. Note bornite (*b*) embedded in large plates of lamellar chalcocite. Upper Ore Horizon, Drill-hole D–12 at 804 ft. × 215.

FIG. 14. Mutual intergrowth of linnaeite (*L*) and chalcopyrite (*cp*). Both minerals partially replaced by chalcocite (*cc*). Note spongy-textured residual linnaeite. Black is gangue. Upper Ore Horizon. Drill-hole D–15 at 610 ft. × 70.

FIG. 15. Intergrowth of bornite and chalcocite, showing bornite (dark gray) replaced by minute reticulating veinlets of chalcocite (white). Upper Ore Horizon, Drill-hole D–12 at 804 ft. × 800.

[10] Lindgren, W.: Mineral Deposits, pp. 945–947, New York, 1928.

is again regarded as typical of supergene chalcocite, and probably of meta-colloidal origin.

Where supergene chalcocite rims large areas of bornite, the progressive replacement of the bornite by chalcocite is often well illustrated. The preliminary attack consists of the penetration of bornite along fractures by comparatively coarse and irregular veinlets of chalcocite. Farther into the chalcocite rim, where replacement has become more organized, the residual bornite is replaced along a delicate triangular lattice pattern, probably controlled by the bornite cleavage. Thus the earlier stage is that of coarse fracture-filling, followed by replacement controlled by the molecular structure of the host-mineral. This mechanism is illustrated in Figs. 10 and 11, photomicrographs taken near the contact of a rim of supergene chalcocite surrounding and replacing bornite. A study of these structures brings out the fact that triangular lattice structures of bornite and chalcocite may be as well developed under supergene as under hypogene conditions, and that the presence of these triangular lattice structures may not necessarily be regarded as a safe criteria of hypogene origin.

Under conditions of post-mineralization stress, the older sulphides may yield and be replaced by younger supergene sulphides along lines of strain, roughly coincident with the fracture-cleavage of the surrounding sediments. Such a condition is illustrated in Fig. 12, a specimen from the sheared beds of the River Lode. A "plaid" pattern has resulted from the replacement of stressed bornite by chalcocite (both supergene). The details of replacement have been controlled by the octahedral cleavage of the bornite, but the elongation of the patterns is coincident with the cleavage and axial plane of the N'Changa syncline.

Many specimens, particularly those from the West Extension, show evidence of a definite time-interval between the supergene replacement of chalcopyrite by bornite, and a later and also supergene replacement of both by chalcocite.

In practically all cases of supergene replacement of chalcopyrite by bornite, chalcocite also is present in abundance. Occasionally, however, examples are seen in which this replacement has reached

completion unaccompanied by chalcocitization. In such cases, bornite frequently attacks the chalcopyrite along definite directions, concentrating upon cleavage intersections and replacing the chalcopyrite until only shreds of that mineral remain, surrounded by massive bornite. The chalcopyrite shreds are still aligned roughly parallel to the original veinlets of bornite. Later, the chalcopyrite disappears altogether. That the bornite of this pattern is supergene is further indicated by the fact that it is commonly observed to grade directly into rim-pattern bornite of undoubtedly supergene origin.

"Graphic" intergrowths. This micro-texture consists of the lobate intergrowth of pairs of minerals, the resulting structure resembling the eutectic pattern of metallurgical products. It occurs in the Rhodesian ores as intergrowths of bornite and chalcocite. Amongst the N'Changa ores the structure is rare; it has been observed only in the core from one drill-hole (D–12), where it occurs in the Feldspathic Quartzite of the Dambo Lode. In the N'Kana Concession it is apparently much more common, and Bateman,[11] who has made a special study of the ores of that Concession, states that: "About every third specimen that contains chalcocite and bornite shows this intergrowth ('graphic' intergrowth) and they are typical of most of the Roan specimens."

Much has been written in the past concerning "graphic" intergrowths, and there is considerable diversity of opinion as to whether they are of hypogene or supergene origin. Bateman considers that in the ores of the N'Kana Concession, this structure has resulted from the simultaneous deposition of primary (hypogene) bornite and chalcocite.

The writer believes that, at N'Changa, this structure has resulted from the simultaneous intergrowth of bornite and chalcocite, probably under supergene conditions. Subsequently, the bornite individuals of this intergrowth were partially replaced by a later generation of chalcocite. The evidence in support of these conclusions may be summarized as follows:

11 Bateman, A. M.: The Ores of the Northern Rhodesia Copper Belt. Econ. Geol., vol. 25, pp. 394–395, 1930.

Graphic intergrowths of the type described above may have originated under any one of four general conditions, viz.

(1) Simultaneous crystallization from hypogene solutions.
(2) Replacement of bornite by hypogene chalcocite.
(3) Simultaneous crystallization from supergene solutions.
(4) Replacement of bornite by supergene chalcocite.

That this structure has arisen by simultaneous crystallization, rather than by a form of replacement of bornite by chalcocite, is brought out by a study of etched surfaces (Fig. 13). Etching with dilute nitric acid, or the examination of unetched surfaces under polarized light, shows that the lobate areas of bornite lie within large individuals of chalcocite having physical continuity. This continuity is brought out by the fact that the lamellae of blue and white chalcocite extend uninterruptedly in parallel orientation well beyond the limits of the graphic structure. The structure is somewhat analogous to that of micro-perthite, in which albite lies intergrown within a large plate of potash feldspar possessing physical continuity.

Had this structure resulted from the replacement of bornite by chalcocite, one might expect the chalcocite, upon etching, to show a mosaic structure similar to that displayed by "rim" pattern chalcocite of typical supergene replacement (Fig. 9). The physical continuity of the chalcocite of graphic areas is, in the writer's opinion, a strong argument against replacement.

The evidence for a later and partial replacement of bornite by chalcocite is brought out by an examination of these structures under high magnifications; many of the bornite lobate areas being traversed by innumerable micro-veinlets of chalcocite (Fig. 15), which upon etching, however, show no physical continuity with the large plates of chalcocite in which the bornite lies.

In view of the fact that graphic intergrowths characterize only a minute proportion of the sulphide ore, and that the remainder of the bornite and chalcocite at N'Changa shows every evidence of a supergene origin, it seems permissible to conclude that the graphic intergrowths are themselves the result of simultaneous

supergene deposition. Dr. Bancroft [12] states, after examination of photomicrographs furnished by the writer showing the graphic intergrowths of N'Changa:

> ". . . such overwhelming evidence as we have collected in this field shows that graphic intergrowth of chalcocite and bornite no longer can be taken as an exclusive index that these minerals are primary but must be regarded as a form of simultaneous crystallization of these two minerals that can also be developed during processes of secondary sulphide enrichment."

Replacement of linnaeite by supergene chalcocite.—Chalcocite, and to a far lesser extent, bornite, replace linnaeite by processes of supergene enrichment. The typical replacement pattern is similar to that of the rim structure exhibited by replacement of bornite by chalcocite. Chalcocite rims linnaeite and replaces it along a network of fine veinlets, bornite often occurring as a narrow selvage at the linnaeite-chalcocite contact, or as an intergrowth in the chalcocite veinlets. It should be noted that, although chalcopyrite and linnaeite almost invariably exhibit mutual intergrowths of simultaneous primary crystallization, bornite appears only as a segregation within the supergene chalcocite near its margins. This is but another of the many indications of the supergene origin of bornite at N'Changa.

A peculiar variation of replacement of linnaeite by chalcocite was observed in specimens of cobalt ore in the feldspathic quartzite from drill-hole D–15 of the Dambo Lode. The form of replacement, apparently characteristic of all specimens from this drill-hole, consists of abundant spongy-textured residual linnaeite within the chalcocite (Fig. 14). This residual material may be traced directly into massive unreplaced linnaeite, and typically forms a continuous layer along the chalcocite-country rock contact, from which it projects in spongy leaf-like pattern into the chalcocite rimming the massive linnaeite. This spongy linnaeite is rarely found in the chalcocite close to the linnaeite contact, but is confined more commonly to the gangue margins.

Chalcocite of this replacement is characteristically of a dark

[12] Bancroft, J. A., Personal communication to the writer.

blue-gray color. Where it occurs as fine veinlets penetrating either the chalcopyrite or chalcocite, examination under high magnifications generally reveals the presence of small amounts of intergrown bornite, indicating a slight excess of iron.

In collaboration with Dr. H. F. Harwood, the writer suggests the following reactions for the replacement of linnaeite by chalcocite under different conditions:

(1) Replacement of linnaeite direct by chalcocite.

$$Co_3S_4 + 6CuSO_4 + 4H_2O = 3CoSO_4 + 3Cu_2S + 4H_2SO_4.$$

(2) If ferric sulphate be present:

$$Co_3S_4 + 2CuSO_4 + 10Fe_2(SO_4)_3 + 12H_2O = 3CoSO_4 + Cu_2S + 12H_2SO_4 + 20FeSO_4.$$

(3) Replacement of linnaeite by covellite, with subsequent conversion to chalcocite:

$$4Co_3S_4 + 15CuSO_4 + 4H_2O = 12CoSO_4 + 15CuS + 4H_2SO_4.$$

(4) If ferric sulphate be present:

$$Co_3S_4 + 2CuSO_4 + 7Fe_2(SO_4)_3 + 8H_2O = 3CoSO_4 + 2CuS + 14FeSO_4 + 8H_2SO_4.$$

The covellite may be subsequently be converted to chalcocite, according to Lindgren's reaction:

$$5CuS + 3CuSO_4 + 4H_2O = 4Cu_2S + 4H_2SO_4.$$

The dark color of chalcocite replacing linnaeite at N'Changa suggests the presence of covellite in solid solution. Its formation by the action of cuprous and ferric salts is suggested by equations 3 and 4, above.

Bieberite ($CoSO_4.7H_2O$) occurs in small quantities at N'Changa, filling fractures in beds immediately underlying the linnaeite-bearing feldspathic quartzite. It has evidently been formed by the hydration and crystallization of cobalt sulphate liberated during the replacement of linnaeite by chalcocite or covellite.

SUMMARY AND CONCLUSIONS.

1. The N'Changa Mine and Extensions constitute one of the principal copper deposits now being developed in Northern Rhodesia.

2. The general geology of the N'Changa District, and of the N'Changa Mine, is briefly outlined.

3. The ores are of the typical disseminated type of Northern Rhodesia. They are clearly epigenetic in origin, introduced after the main period of regional metamorphism. Their source is believed to be that of the N'Changa Younger Red Granite, and possibly that of the Younger Gray "Granite."

4. The gangue minerals consist of the partially replaced country rock, and of minor amounts of hydrothermal products consisting of quartz, microcline, white mica, and colorless chlorite. Some calcite and dolomite may have been introduced at this stage.

5. Primary mineralization consists of chalcopyrite, pyrite, and linnaeite, chalcopyrite being the most abundant. These sulphides are referable to a single period of mineralization, but the linnaeite is apparently slighter later than the chalcopyrite. Pyrite occurs mainly as marginal facies of the chalcopyrite bodies.

6. Subsequent supergene solutions enriched the deposits with abundant bornite and chalcocite.

7. Practically all the bornite and chalcocite of the N'Changa deposits is of supergene origin, resulting from the replacement of primary sulphides by meteoric waters rich in sulphates of copper and ferric iron. The bulk of the sulphide ore consists of chalcocite.

8. The majority of replacement micro-structures are those of the well known "rim" pattern, in which chalcocite or bornite replaces the primary sulphides at their margins.

9. Bornite occurs either as a comparatively large-scale replacement of chalcopyrite, or as a marginal phase at the chalcopyrite-chalcocite contacts, where it represents an intermediate stage of diminishing iron and sulphur. Less commonly, bornite forms the earlier stage of supergene replacement followed by a definitely later stage of replacement by chalcocite.

10. A study is made of "graphic" intergrowths (rare at N'Changa) between bornite and chalcocite. Etched surfaces reveal the bornite individuals embedded in large plates of physically continuous lamellar chalcocite. Simultaneous intergrowth of bornite and chalcocite is inferred, though probably under supergene rather than hypogene conditions. A later generation of chalcocite has partially replaced some of the bornite. The etch structure of the chalcocite in these graphic intergrowths is contrasted with the micro-mosaic lamellar pattern exhibited by etch surfaces of chalcocite of typical rim-replacement habit.

11. The high-grade cuprite ore which forms an appreciable proportion of the N'Changa West Extension ore body, is a direct oxidation product of chalcocite with no intermediate stage. Malachite and limonite marginally replace much of the cuprite.

12. Native copper, an uncommon constituent of the N'Changa deposits, has arisen by reduction of both chalcocite and cuprite.

13. The linnaeite appears to favor those formations rich in coarse, clastic feldspar grains, such as the Feldspathic Quartzite and the Footwall Arkose. The abundant kaolin derived from the decomposition of these sediments may possibly have acted as a precipitant.

14. The mechanism and chemistry of the extensive replacement of linnaeite by chalcocite are discussed. This replacement shows some unusual features, and several new chemical reactions are put forward.

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CHRYSOTILE ASBESTOS: II, CHRYSOTILE SOLUTIONS.

GEO. W. BAIN.

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INTRODUCTION.

KEITH's studies indicate that chrysotile veins occur as a filling of open fractures in peridotite, dunite, and serpentine, and that the amount of filling derived by direct recrystallization is insignificant. Older theories of formation indicate recrystallization from serpentinized walls. Chrysotile veins in filled fractures in unserpentinized dunite of northern Vermont and adjacent parts of Quebec call for an adequate external source of filling wherever asbestos is found.

Field Studies and General Relationships.—The Thetford Mines, Black Lake and Danville districts in Quebec had been studied in-

tensively in late years without yielding much new information on the origin of asbestos. Accordingly field work was conducted in the comparatively unstudied parts of the serpentine belt between Eastman in Quebec and Westfield in Massachusetts. Eighty serpentine bodies were mapped in detail and eight others studied; some present extremely complex relations but about fifty per cent. have talc at one end of the mass and asbestos at the other. Some are changed completely to talc; pseudomorphs after asbestos are common. A few bodies have magnetite and carbonate or carbonate only at the end farthest removed from the talc. Others are relatively unchanged and two have been almost completely granitized.

Certain petrographic peculiarities of serpentine and dunite of the belt facilitated field work. Serpentinized rock almost invariably weathers white and resists weathering better than unserpentinized rock; peridotite and dunite weather red or light green in color and are much more easily affected by weathering agents. Primary flow structure is common and accelerates weathering. Thoroughly serpentinized peridotite almost invariably shows flow or fracture cleavage or both, and is much tougher than unserpentinized stone.

Materials of the Vein Filling.—Fibrous minerals of the veins include magnetite and magnesite as well as chrysotile. Chemical composition and physical properties of the chrysotile show related changes; for example, flexibility of fiber increases with total water content up to a maximum of 13 per cent. The composition of chrysotile is usually given as $H_4Mg_3Si_2O_9$; this may be written $(3Mg_2SiO_4 . H_2O) . (H_4SiO_4 . H_2O)$ and the variable water is regarded as water of crystallization.

The problem of the origin of filling for chrysotile veins is therefore the origin of solutions containing $FeO . Fe_2O_3$, $MgCO_3$, $Mg_2SiO_4 . H_2O$ and $H_4SiO_4 . H_2O$. The source of these constituents can be shown for every lens containing introduced magnetite, magnesite, chrysotile, or serpentine, and occurring between Eastman in Quebec and Westfield in Massachusetts. Presentation of the total evidence involves useless duplication and only a

few specific deposits will be described in sufficient detail to illustrate each type of source.

SOURCES OF FILLING.

Sources of filling for the veins may be classified as:

a. Serpentinization processes.
b. Conversion of serpentine to talc.
c. Granitization.

Each is a constant volume change in this serpentine belt, and volume balance is maintained by removal of material.

Serpentinization Processes.

Serpentinization is one of the most general processes in the serpentine belt. Most peridotites and dunites show some serpentinization; alteration amounts to about thirty per cent. in a few masses and is complete in many.

Volume Relations.—Dunite crosses the Hazen road about ¾ of a mile west of Lowell, Vt. Serpentinization is confined to fracture cleavage, which is well preserved and marked by dark serpentine bands through the dunite. The serpentine widens at intersection of two cleavages and dunite fragments have rounded corners due to progressive serpentinization inward from the cleavage planes. Blocks of the fracture cleavage are not displaced by this excess serpentinization on the corners but show closing along the stress direction and opening at right angles to it (Fig. 1).

Serpentinization of dunite represents a mass increase of 31.2 per cent. and a specific gravity decrease of 23.5 per cent or a volume increase of 71.6 per cent. Volume increase is accommodated partly by spaces of the fracture cleavage but mostly by removal of serpentine in spent solutions.

Serpentinization progresses from the fracture cleavage planes into the fracture cleavage blocks; it occurred simultaneously with opening of the fissures. Keith has shown that the chrysotile veins occur as fillings in fissures produced by adjustment of stresses in the fracture cleavage blocks outside the zone of extensive serpentinization at Belvidere Mountain and altogether outside it at Lowell. Deposition of chrysotile accompanied produc-

tion of fracture cleavage characteristic of the serpentine and dunite masses and contemporaneous with serpentinization of parts of them. Some of the chrysotile therefore could be the excess serpentine removed in solution from the serpentinized areas.

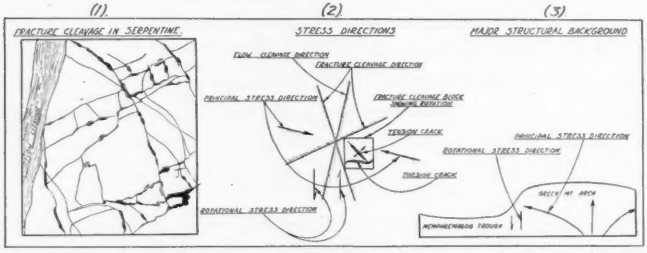

FIG. 1. Fracture cleavage in dunite at Lowell. (*1*) Drawing of a polished specimen of dunite showing both fracture and flow cleavage. The black areas represent serpentine along the fracture cleavage. Observe that the blocks of the fracture cleavage are closed up along the stress direction and are opened slightly at right angles thereto. (*2*) Rotation of the fracture-cleavage blocks and the flow-cleavage direction is shown on diagram in the central part of the figure. (*3*) Major structural features responsible for the stresses are shown on diagram at the extreme right.

Mass Relations.—Mass relations are entirely within the possibility range. Few asbestos deposits contain over five per cent. of fiber. Most serpentinized dunite masses of the belt are 30 per cent. changed. Serpentinization renders 21.5 per cent. of the altered mass available for vein filling so that a comparatively small alteration zone could furnish enough material to fill the spaces in dunite outside it. Excess serpentinizing solutions commonly accompany the serpentine-bearing types and produce variable wall alteration, as at the Gallagher Mine; at other places they appear to have been completely neutralized by the dunite when it was changed to serpentine, as in the case of the deposit northeast of Lowell.

Conversion of Serpentine to Talc.

Two large lenses of serpentine, dunite and saxonite in Waitsfield, Duxbury, and Moretown, pitch to the north and have talc

at their south end or under side and asbestos at their north end or top. A similar relation exists at the Rochester Talc Mine. Talc occurs at the southeast end of the Rochester Verde Antique quarry; fibrous magnesite and chrysotile occur in the upper part at the north end. This same relation recurs at so many places, including the deposit of the Vermont Asbestos Corporation on Belvidere Mountain, that it suggests a genetic relationship between talc and asbestos.

Dunite and saxonite do not alter directly to talc. Talc showing fracture cleavage blocks rounded by progressive serpentinization, pseudomorphs of talc after picrolite and brittle asbestos, talc with flow cleavage of verde antique serpentine, and residual areas of serpentine between veins with talc borders, all indicate that serpentinization precedes the change to talc.

Volume Relations.—Volume relations in the serpentine to talc alteration are illustrated best in a small lenticular mass of dunite, serpentine, and talc in southwest Newfane, Vermont. A lenticular dunite intrusive outcrops on a high hill so that the ends and sides are well exposed; talc forms a thin wall to the serpentine and dunite core and occurs as a great keel-shaped deposit below it (Fig. 2). Fracture cleavage blocks in the talc preserve the

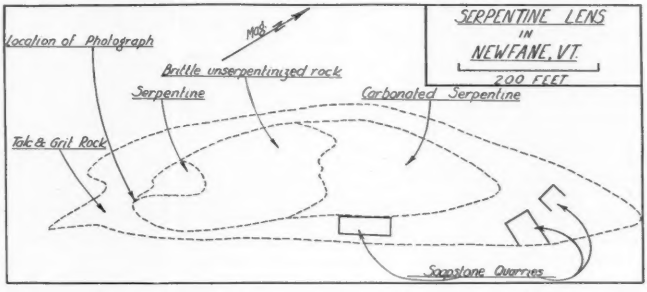

FIG. 2. Map of lenticular serpentine-dunite mass in Newfane, Vt., typical of small masses. Talc, soapstone and grit-rock surround a serpentine and dunite core; that they form a great keel-shaped mass beneath the core is shown on the cliff at the south end (Fig. 3) and in the soapstone quarries on the east side of the lens.

rounded form imparted to them by progressive serpentinization. The rock already had both fracture and flow cleavage when talc alteration began, and fracture cleavage openings were entirely filled by left-over serpentine so that solutions causing talc alteration soaked more or less uniformly into the bottom of the lens and along the sides of it. Consequently many fracture cleavage blocks are half serpentine and half talc; cleavage planes cross the talc-serpentine contact in perfect continuity and show conclusively that no expansion accompanied alteration to talc (Fig. 3).

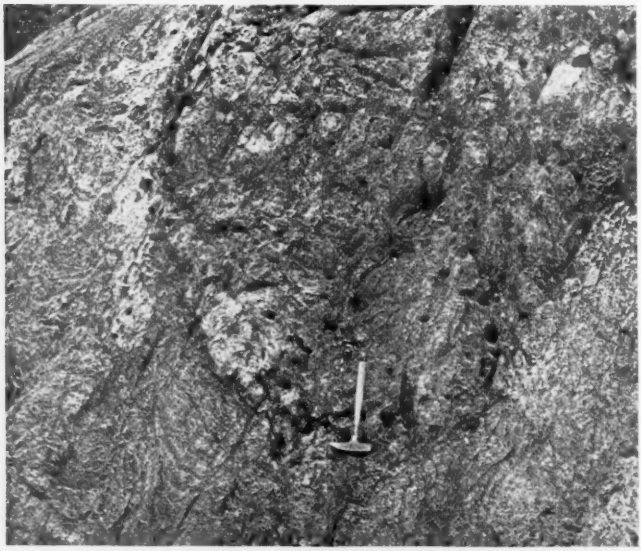

FIG. 3. Photograph of the southward facing cliff on the Newfane serpentine lens. The hammer lies on the contact between light talc below and dark serpentine above. Observe the elliptical fracture-cleavage block to the left of hammer; one half is talc and one half serpentine; no displacement of the fracture-cleavage boundary can be seen. Observe also the distinctness of this "chemical metamorphism" contact and its independence of fracture systems.

Composition of talc is given as $H_2Mg_3Si_4O_{12}$; it may be written $(3MgSiO_3).(H_2SiO_3)$. The change of serpentine to talc requires addition of $2H_2SiO_3$ and removal of $2H_2O$ or the water of crystallization in the serpentine; this represents a mass increase of 21.5 per cent. Talc has approximately 6 per cent. higher specific gravity than serpentine, so that the volume increase is only 15 per cent. Since no volume change occurs in the body undergoing alteration, 15 per cent. of the original serpentine must be removed in solution.

Mass Relations.—Talc alteration liberates 15 per cent. of the serpentine changed. If 5 per cent. fiber is considered an average deposit, then a talc mass would free enough serpentine to make an asbestos deposit three times the size of the talc body. All asbestos deposits in the belt studied have associated talc in excess of one third the amount of fiber deposits.

Granitization.

Granite intrudes serpentine at Westfield, Mass., at Roxbury, Lowell and Westfield in Vermont, and at Trowsers Lake, south of Eastman, in Quebec. The Roxbury intrusive has deuteric fuchsite and mariposite; chromium in these unusual minerals was acquired probably by assimilation of the chromiferous serpentine

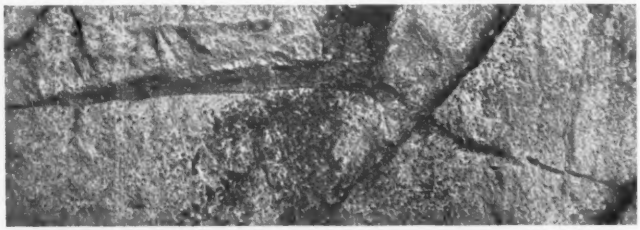

FIG. 4. Photograph showing an orthoclase anthophyllite vein in the Trowsers Lake granite. The vein is offset twice near its right end. The quartz and feldspar crystals along the line of displacement show no deformation; this indicates that the veins were opened before the feldspars were formed and that the present granite is a replacement of some earlier rock. The fibers in the veins may be seen in the horizontal part of the vein.

lens in the granite or incomplete replacement of serpentine by granite. Granites at Lowell, Westfield, and Trowsers Lake are characterized by sheafs and bunches of anthophyllite.

Serpentine, and talc pseudomorphous after serpentine, on the north shore of Trowsers Lake, are intruded by dikes of white to light gray granite. A large mass of granite occurs in the middle of this serpentine body on the south shore. Veins with the woody structure of picrolite or the fibrous structure of chrysotile are numerous in the granite on the south shore (Fig. 4); they consist of anthophyllite and acicular orthoclase. Occurrence of structures so foreign to orthoclase and so characteristic of chrysotile immediately suggests replacement of the latter.

The granite is medium textured, has massive structure and is composed of approximately 70 per cent. feldspar (orthoclase and albite-oligoclase in equal amounts), 25 per cent. quartz, 4 per cent. anthophyllite and 1 per cent muscovite. Anthophyllite occurs as fibers penetrating feldspar and quartz, along with radiating groups of muscovite and around matted aggregates of anthophyllite (Fig. 5). The penetrating fibers appear to be replacing the feldspar and quartz but distribution about central aggregates points to recrystallization from the matted nucleus. The fresh condition of the feldspars indicates a recrystallizing solution in equilibrium with them.

The veins in the granite have the complementary walls of chrysotile. The fibers, however, seldom reach from wall to wall. Acicular orthoclase predominates over anthophyllite in about the same proportion that it does throughout the massive part of the rock. Absence of deformation structures in minerals of the walls of the veins made by the opening of fissures, even where a vein is offset, shows that the wall minerals were formed after the veins were made in some rock composed of other material. The early age of the veins and the equilibrium of the anthophyllite making solutions with the feldspars seem to indicate that reorganization and feldspar formation are due to the same solutions.

Anthophyllite is distributed in approximately equal amount throughout this granite. Proximity to a vein does not affect the amount. Erratic distribution might suggest assimilated zeno-

liths; uniform distribution suggests an incompletely replaced serpentine mass.

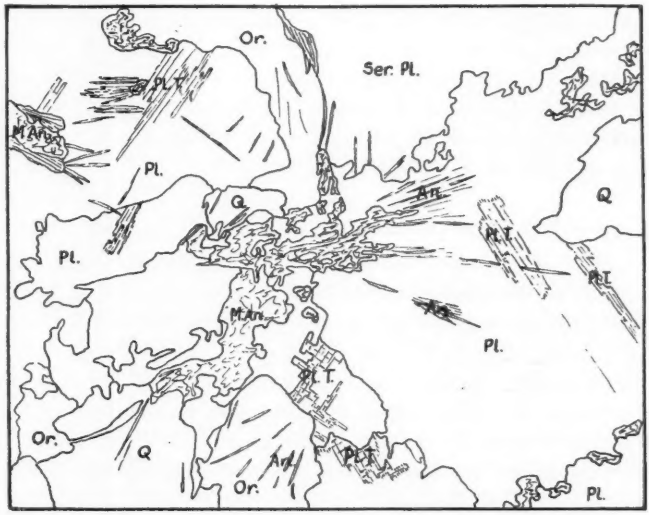

FIG. 5. Drawing from a photomicrograph showing anthophyllite in Trowsers Lake granite. × 65. The granite is composed of occasional sericitized andesine feldspar (*Ser Pl*) of an early generation, later albite-oligoclase (*Pl* and *Pl T*) with late-stage orthoclase (*Or*) and quartz (*Q*). Alkalic rims surround the soda-lime feldspars adjacent to the quartz and orthoclase. Anthophyllite occurs as irregular matted aggregates (*M An*) from which sheaf-like anthophyllite (*An*) radiates into all surrounding minerals, especially the soda-lime feldspars. This sheaf-like anthophyllite seems to be a late deuteric recrystallization product.

Radial aggregates of muscovite and anthophyllite represent a further stage in reorganization of the original material, conversion to minerals more characteristic of granite, and further expulsion of magnesium from the mass.

Volume Relations.—Granitization of serpentine with complete preservation of former serpentine structures indicates replacement at constant volume. The mass of granitized rock therefore rep-

resents the amount of serpentine removed and the amount available from this source to be deposited in fissures in non-granitized parts of a deposit. Known granites in serpentines are uncommon and this source of chrysotile solution, although important at Trowsers Lake in Quebec and at Westfield, Lowell, and Roxbury in Vermont, is probably not the most significant one. However, it must be considered, inasmuch as granitization would furnish sufficient serpentine to solutions to make an asbestos deposit twenty times the size of the area granitized.

MOVEMENT OF THE SERPENTINE-DISSOLVING SOLUTIONS.

Doubt might exist that solutions leaving the alteration zones actually carry substances to make serpentine minerals. The serpentinization reaction might be supposed to be due to interchange of materials along a contact. Also dissolved magnesium orthosilicates might diffuse back towards the source of the solutions producing the alteration. Field observations and petrographic evidence indicate that neither of the above possibilities appear to have taken place and that reaction and solution movement are unidirectional.

Contact Relations.

Wallrock alteration along serpentine bodies is essentially the same throughout the belt. All wallrocks become heavily chloritized and impregnated with magnetite. The chlorite commonly changes further to talc, actinolite and biotite. Epidote (pistacite) predominates over chlorite along two Roxbury masses.

Wall alteration along the Moretown lens at the Duxbury talc mine is typical. The lens is about one mile long and five hundred feet wide and is intrusive into muscovite and biotite schist and gneiss (Fig. 6). The talc deposit at its south end pitches northward under the serpentine at approximately 30°. The west wall cuts across the banding of the gneiss marked by quartz stringers. Feldspathic and micaceous bands in the gneiss, and rarely even the quartz, are replaced by chlorite in diminishing intensity up to three feet from the contact. Materials removed, when the chlorite was deposited, include chiefly alkalies and alumina; materials in-

troduced include chiefly magnesium and iron. Magnesium and iron were removed from the adjacent serpentine during its alteration to talc and evidently some stray solutions moved out into the walls and precipitated chlorite, a kindred mineral to serpentine.

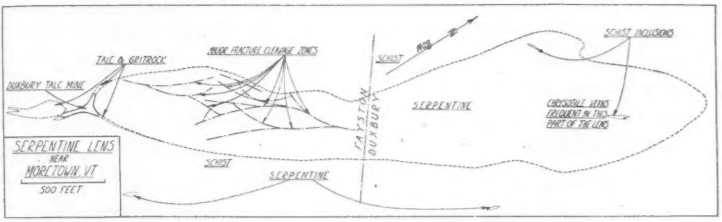

FIG. 6. Map of the Moretown serpentine lens showing the talc mine at the south end and major fracture zones. The talc mine follows the talc down under the lens at about 25° northeastward. The intersection of the fracture cleavages pitches down at the same angle and their intersection with a horizontal plane gives the acute angle between them, as seen in the south part of the lens in Fayston.

Alkali and alumina minerals are completely lacking in the talc deposits, so that back diffusion or exchange along the solution paths was insignificant if not totally absent, and serpentine was removed upward and outward only.

Backward Diffusion.

Serpentine alteration to talc proceeds upward from the bottom of the lens or serpentine mass. This is shown clearly in the deposits in Newfane, and the numerous ones in Windham, Chester, Cavendish, Baltimore, Stockbridge, Rochester, Granville, Roxbury, Waitsfield and Duxbury. Typical biotite schist closes off the Newfane talc deposit on the bottom. Granitic gneiss underlies the Baltimore soapstone deposit and a thin biotite band envelops the walls. Typical biotite schist of the region underlies the talc lens of the Greely Talc Mine in Stockbridge. Sericite schist occurs below the East Granville talc deposit. Biotite schist and gneiss cut off downward extension of the talc deposits southeast of the Central Vermont Railroad at Roxbury. Sericite and

biotite schist and gneiss underlie talc at the south end of the Waitsfield lens and at the Duxbury talc mine. No enrichment of ferromagnesian minerals in wallrock was evident on the underside of any of the talc bodies; typical regional rocks, with some slight additional sericitization, prevailed. Inasmuch as alteration worked up from below, it is assumed that the solutions likewise came from depth. Absence of increase of ferromagnesian constituents in wallrocks under so many serpentine-talc masses is strong evidence against backward diffusion of the serpentine-bearing solutions.

Petrographic Evidence.

Two definite reaction series for olivine alteration have been recognized in this work. One reaction series is due to chemical alteration processes and the other to recrystallization processes. Each series represents an advancing alteration condition. Alteration reaches a maximum advance; as it retreats it leaves almost no minerals as evidence of recession. During recession of alteration processes, any part of a serpentine-bearing solution which tended to diffuse backward would become fixed as one of the less advanced members of the reaction series. If serpentine solutions diffused back into the talc zone, serpentine replacements of talc would be expected.

The Hydrothermal Reaction Series.—The hydrothermal reaction is as follows:

Olivine → Serpentine
"Rock" → Chlorite
→ Talc → Actinolite → Hornblende
→ Talc → Biotite → Muscovite

Assuming that backward diffusion is possible, talc should replace actinolite and biotite during backward diffusion in the recession stage of alteration. Beautiful actinolite metacrysts occur in the outside and deep parts of the talc at one Roxbury deposit, at the Rochester Verde Antique quarry, the Duxbury talc mine and in one talc mine at Chester. The faces of the crystals are perfectly smooth and unchanged.

Backward diffusion, if it occurs, should leave hornblende or the last mineral of the reaction series, as a band along the solution

channel or rock zone through which the solutions passed. Hornblende zones below talc and outside the limits of the original serpentine are almost unknown and the only ones observed in association with talc are in the granitized deposit at Rowe in Massachusetts. Intrusion is so complex at this locality that it is impossible to distinguish the original outline of the deposit.

Complete lack of replacement of a later member of the reaction series by an earlier one and absence of the end member of the reaction series in the country rock under serpentine and talc masses are evidences against back diffusion.

Recrystallization Reaction Series.—The recrystallization reaction series should not be confused with the hydrothermal series. It is as follows:

Olivine → Deuteric serpentine → Anthophyllite → Muscovite

These reactions take place almost *in situ* and in the absence of abundant orthosilicic acids. They are therefore of little importance in the study of movement of solutions.

MOVEMENT OF THE CHRYSOTILE-DEPOSITING SOLUTIONS.

Keith has shown that chrysotile veins occur in tension fractures perpendicular or nearly perpendicular to the flow cleavage *direction* in *massive* serpentine and dunite. The veins are predominantly filled fissures, and the filling material originated outside the immediate vicinity of the deposit. Chrysotile-dunite-serpentine relations, chrysotile-serpentine-talc relations and the zonal distribution of the chemical reaction series minerals, indicate that the solutions not only could have formed during serpentinization and alteration of serpentine to talc, but did originate as a result of these alteration processes and contemporaneous with development of fracture cleavage.

Wallrock Influence.—Absence of chrysotile deposits outside of massive serpentine and dunite is due to the physical properties of wallrocks. Schists are either too fissile or too tough to develop tension cracks perpendicular to the flow-cleavage direction; instead they develop flow cleavage and lack openings for the solutions. Granite is commonly stronger and tougher than the serpentines

and dunites and lacks fissures to act as hosts for the solutions. Also at Moretown, serpentine solutions leaking out into feldspathic rocks reacted to give chlorite and epidote. Chrysotile-bearing solutions, therefore, are not in equilibrium with feldspars and so far as has been determined in this study, are in equilibrium only with serpentine, olivine and rarely pyroxene. Reaction with feldspars gives chlorite veins and streaks.

Chrysotile-Serpentine-Dunite Relations.—Serpentinization in every lens examined is most complete immediately adjacent to the talc keel of a lens, and extends upward along the more prominent fracture-cleavage planes. Rarely slip fiber asbestos is deposited, especially if flow cleavage develops, as at the mine of the Vermont Asbestos Corporation on Belvidere Mountain, or as in a small lens southwest of North Troy, or at the north end of the Waitsfield lens and at the Rochester Talc mine. Commonly however, asbestos is deposited as chrysotile in tension or drag torsion cracks leading off from fracture cleavage. This is the mode of occurrence at Lowell, at the Gallagher Mine, and at Moretown.

Areas of serpentinization have a volume increase over and above the space produced by fracture cleavage. Fracture cleavage produces available space outside areas reached by serpentinizing solutions. The spent solutions move towards the area of least pressure or where serpentinization to use up fracture-cleavage space is least active.

Main channels, or channels of active circulation of serpentine producing and carrying solutions, do not contain much chrysotile or asbestos. Asbestos is deposited from these solutions when they get away from the main channels into stagnant by-passes and dead-end fissures. These associations indicate relationship between the place where the serpentinization solutions could originate and the place of precipitation of chrysotile.

Chrysotile-Serpentine-Talc Relations.—Occurrence of talc in the lower part of a lens and chrysotile in the upper part, as at the Greely Talc mine, the Rochester Talc mine, the Rochester and Roxbury verde antique quarries, the Waitsfield lens, the Moretown lens and the Vermont Asbestos Corporation deposits, is no

chance distribution. Talc alteration represents great chemical change, volume increase, and removal of material. Slip fiber asbestos and chrysotile in the upper part of the deposits is of foreign origin and fills fissures. The occurrence represents a redistribution of materials due to pressure developed by the volume-increasing hydrothermal processes in operation in depth.

Zonal Distribution of Reaction Series Minerals.—Alterations that are accompanied by volume increase but where no increase of the entire body occurs, must be accompanied by a distributed removal of material. Alterations of dunite to serpentine and talc are of this type. It has been shown already that backward diffusion of solutions to the inner zone of the reaction series minerals does not occur. Removal of the solutions must be towards the outer zone of reaction-series minerals. The hydrothermal reaction series for olivine is:

Olivine → Serpentine → Talc → Actinolite → Hornblende

This represents increasing volume in the later members and the solutions must move in the opposite direction to the increasing volume under pressure developed by this change. They pass out through serpentine towards the olivine zone and occupy spaces produced by dynamic movements in the zone of fracture similar to where the chrysotile deposits are found.

SUMMARY AND CONCLUSIONS.

Chrysotile occurs in the least altered part of a lens. Slip fiber has a more general distribution.

Serpentine ($H_4SiO_4.Mg_2SiO_4.2H_2O$) must be removed in large amounts from the most altered parts of any talc-serpentine-dunite mass. The amount which is so removed in any specific mass is entirely adequate to make the chrysotile deposits that occur in that same intrusive body.

Pressure relations and zoning according to the reaction series point clearly to movement of the pregnant solutions from areas of alteration to the place of occurrence of the chrysotile deposits.

Association of a fracture cleavage system in a massive serpentine-dunite mass which nearby, either below or along the length

of the fracture-cleavage system, has a highly serpentinized rock or talc deposit, seems to be the primary requisite for one of these chrysotile deposits.

The silicon acids that produce the alteration and altering solutions are regarded as being of magmatic origin and associated in some way with the granite intrusives, but all other constituents of the solutions are regarded as being secreted from rocks through which the solutions pass.

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NOTES ON A KENNECOTT TYPE OF COPPER DEPOSIT, GLACIER CREEK, ALASKA.

ALAN M. BATEMAN.

INTRODUCTION.

A RECENT discovery of interesting copper ore at Glacier Creek, Alaska, disclosed another deposit of the Kennecott type of metallization. Since it lies some 35 miles from Kennecott, and consists of generally similar ore, it indicates a widespread distribution of this type of metallization. The ore itself is unusual, consequently a few notes about the deposit may be of interest.

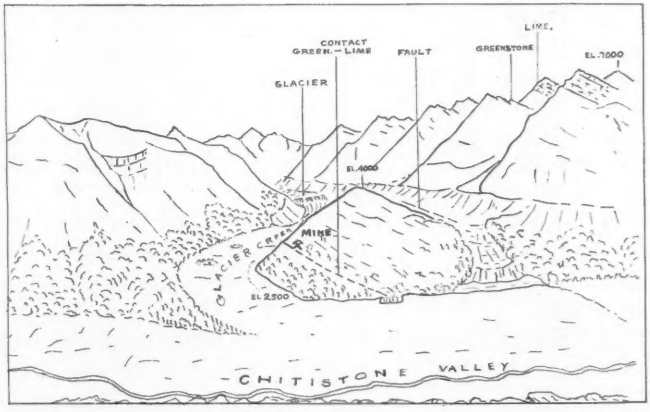

FIG. 1. Panoramic sketch looking up Glacier Creek, with the glacier in the distance. Faulted block of limestone in center, with mine just above normal greenstone contact; hills to the right composed of greenstone with overlying limestone forming castellated peaks at extreme right. Slightly modified from sketch drawn by W. A. Richelsen.

The deposit lies at an elevation of 3,100 feet on the west side of the valley of Glacier Creek (Fig. 1), a swift tributary of the Chitistone River, which, in turn, forms a part of the Copper

River drainage. It is readily accessible by horse or on foot, except for the difficulty of fording swift, treacherous, glacial streams. The region is mountainous and rugged, with flat-bottomed, steep-sided glacial valleys whose walls rise precipitously to elevations of 6,000 to 8,000 feet. Most of the tributary streams are headed by glaciers.

The property was worked for a year by the Kennecott Copper Corporation but was abandoned in 1930. It was studied by the writer, in company with BeVan Presley [1] and W. A. Richelsen,[2] in the summer of 1930.

GENERAL GEOLOGY.

The general geology of the region in the vicinity of Glacier Creek has been described recently by Moffit,[3] whose map includes a part of the Glacier Creek section. The mapping was completed, however, before the discovery of the copper deposit. The regional geology is, in general, similar to that at Kennecott.

Rock Formations.—The formations in the vicinity of the property include only the Triassic Chitistone limestone, the underlying Nikolai greenstone of Permian or Triassic age, and recent deposits, chiefly fluvio-glacial.

The greenstone here consists of about 5,000 feet of basaltic lava flows, altered for the most part, and stained widely with copper minerals. It forms the middle and lower slopes of the valley walls.

The Chitistone limestone in this vicinity is about 2,000 feet thick and is separated from the underlying greenstone by a three-foot shale band. It forms the tops of the mountains and its blocky weathering yields imposing castellated peaks. The Chitistone limestone here, as at Kennecott and elsewhere in this region, has undergone partial dolomitization. All the commercial ore is confined to the Chitistone formation.

The bottom of the limestone on the west side of Glacier Creek

[1] Manager, Kennecott Copper Corp., Kennecott, Alaska.

[2] Chief Engineer, Kennecott, Alaska.

[3] Moffit, F. H.: Notes on the Geology of the Upper Nizina District, Alaska. U. S. Geol. Surv. Bull. 813-D, pp. 143–163, 1930.

lies at elevations of from 4,000 to 6,000 feet; the greenstone extends down to the creek level at an elevation of 2,500 feet. However, where Glacier Creek joins Chitistone River, a large wedge-shaped slice of the limestone, some 7,000 feet long, 2,000 feet wide, and about 1,300 feet high (Fig. 1), has been relatively down-faulted several thousand feet so that the limestone touches the river gravel at the north end of the block and, due to its dip, lies 700 feet above the river at its south end. The ore deposit lies within this faulted limestone block.

The sequence of lower beds of the Chitistone formation is the same as at Kennecott, namely, greenstone, shale, pyritic limestone, black limestone, gray limestone, and gray dolomite.

Structure.—A broad, shallow syncline trends northwesterly throughout this region. Kennecott lies on its southwesterly side and Glacier Creek on its northeastern limb, some 35 miles southeast of Kennecott. The formations therefore strike northwesterly and dip gently (15°–20°) to the southwest.

A great thrust fault with a southwesterly dip has been followed across the region in a northwesterly direction for some 15 miles.[4] Its southward extension is up Glacier Creek. Opposite the mouth of Glacier Creek is an imposing spectacle, shown on a grand scale on the steep valley side, of the underlying Nikolai greenstone over-riding the overlying Chitistone limestone. A few hundred feet of the lower Chitistone beds are doubled sharply under themselves on the hanging wall surface of the fault. It must have a displacement of several thousands of feet. This great thrust crosses the corner of the mountain at the mouth of Glacier Creek. The limestone block (Fig. 1) that was previously mentioned as containing the ore deposit lies beneath it, and lower greenstone lies above it. The normal greenstone-limestone contact above the fault lies some 2,500 feet vertically above and west of the similar contact in the detached block. Consequently, the throw of the fault must be several thousand feet and the displacement along the fault surface much greater.

Within the block, the limestone beds are much disturbed by

[4] See also Moffit, *op. cit.*, plate 3.

minor faults (normal and reverse) whose strikes are at high angles to the trend of the great thrust. It is along these minor faults that the copper metallization occurs. The minor faults are probably contemporaneous in age with the great thrust fault and resulted from the jostling sustained by the underlying block at the time of the major movement.

There has also been considerable post-mineral minor faulting that dislocated the ore.

ORE DEPOSITS.

Character of Ore.—The ore exposed is practically identical with that at Kennecott. It is high-grade copper ore with appreciable silver content, consisting chiefly of chalcocite and covellite but with more enargite, bornite, and chalcopyrite than the Kennecott ore. Masses of pure sulphide ore are common, but for the most part the copper minerals occur as blebs or bunches inclosed in carbonate rock. A few small shipments have been made of hand-sorted "high grade" that yielded about 60 per cent. copper.

Nature of Deposits.—The ore disclosed occurs in steeply inclined narrow fissures and along bedding planes in the limestone and dolomite beds of the Chitistone formation. The types of deposits are almost identical with those at Kennecott except that they are smaller and more discontinuous.

The fissure vein ore is in thin bands of copper sulphides that enlarge here and there into irregularly shaped bunches up to a few feet in diameter. It is "spotty ore." The fissures have little continuity; they lack virility and weaken and fade abruptly, or terminate against bedding planes, or are cut off by small post-mineral faults.

The bedding plane ore consists of thin bands or bunches of sulphide that extend out along favorable bedding planes from either side of cross-cutting fissures. Unfortunately, the ore fades out along the bedding within short distances from the intersecting fissures. Its distribution up and down the bedding planes likewise lacks continuity.

Insufficient ore was developed to justify the initiation of expensive operations in this remote locality.

The Ores.

The ore consists almost exclusively of sulphides of copper; pyrite is rare, and introduced gangue minerals are absent. Chalcocite makes up about 75 per cent. of the ore minerals; covellite is next in abundance; enargite is common, and there are appreciable amounts of bornite and a little chalcopyrite. Some luzonite has also been identified. The chalcocite, like that of Kennecott, is of especial interest.

Chalcocite.—Three varieties of pure chalcocite may be recognized in hand specimens, namely, (1) "steely," (2) fine crystalline, and (3) coarse "platy" chalcocite. The last is rather unusual. It resembles granular magnetite. It is distinctly granular and is made up of individual grains, each with a cleavage surface from 1 to 5 mm. across, arranged in haphazard pattern. The specimen scintillates in the light like a piece of diorite. All three varieties may be intimately admixed with covellite.

Under the polarizing reflecting microscope the two kinds of chalcocite may be readily distinguished, namely, the anisotropic or common orthorhombic chalcocite, and the isotropic or uncommon isometric chalcocite. The Glacier Creek deposits, therefore, constitute another occurrence of natural isometric chalcocite.

The *isometric chalcocite* is found only in those specimens in which covellite is present. It may make up the whole of the specimen or only part of it. It remains isotropic under crossed nicols. This means that it has been formed at a temperature above 91° C. and its inversion to the normal chalcocite has been prevented by the presence of 8 per cent. or more of covellite in solid solution. Numerous microscopic laths of covellite are scattered through the chalcocite and are of the type that has been formed by ex-solution.[5]

The *orthorhombic chalcocite* is prominently anisotropic under crossed nicols. All the "platy" chalcocite referred to above is of the orthorhombic class, as is also much of the steely variety. Orthorhombic and isometric chalcocite may occur in the same

[5] Bateman, Alan M. and Lasky, S. G.: Chalcocite-Covellite Solid Solution and Ex-solution. ECON. GEOL., vol. 27, pp. 52–86, 1932.

specimen. Orthorhombic chalcocite may indicate that it has been formed (1) at a temperature above 91° C. and inverted to the orthorhombic form upon cooling; (2) that it was formed originally as orthorhombic chalcocite by hot solutions at a temperature below 91° C.; (3) that it formed from cold surface waters as supergene chalcocite. This orthorhombic chalcocite is intimately associated with the isometric, which suggests strongly that they were both formed from hot solutions and that the orthorhombic variety is hypogene, not supergene. This conclusion is further substantiated by etch reactions. When solutions of HNO_3 or KCN are applied to the polished surface of the orthorhombic variety a triangular or isometric etch pattern may develop. This shows that such chalcocite has an inherited isometric structure which may have been inherited from ancestral high-temperature chalcocite or from some other isometric mineral that it may have replaced. Since there is no evidence to indicate, and much to oppose, that this chalcocite has been formed by replacement of another isometric mineral, the inference is highly probable that the isometric etch pattern is inherited from ancestral isometric or high-temperature chalcocite. In addition, some of this orthorhombic chalcocite is lamellar, which is considered by Schneiderhöhn [6] proof of an inversion from the isometric to orthorhombic system. Consequently it is considered that this orthorhombic chalcocite is also hypogene and was originally formed at temperatures above 91° C.

Some of the chalcocite yields upon etching a rectangular (orthorhombic) etch pattern. Also, some of the orthorhombic and isometric varieties yield an irregular etch pattern resembling "crackled porcelain," considered by Lindgren to indicate original colloidal deposition—a mode of formation considered probable for the Kennecott chalcocite.[7]

Covellite.—The covellite occurs massive or as specks disseminated in chalcocite. Under the polarizing reflecting microscope,

[6] Schneiderhöhn, H., and Ramdohr, Paul: Lehrbuch der Erzmikroskopie, vol. II, pp. 285–288. Berlin, 1931.

[7] Lasky, S. G.: A Colloidal Origin of some of the Kennecott Ore Minerals. Econ. Geol., vol. 25, pp. 737–757, 1930.

the massive variety is seen to be made up of a felted mass of interlocking covellite laths, set in a sparse matrix of bluish isometric chalcocite. Such laths for the most part are slender and small with average widths of 0.02 mm. and have high interference colors.

The disseminated covellite ranges from sparse slender threads imbedded in orthorhombic chalcocite and visible only under high magnifications, to stout broad laths and plates up to 0.35 mm. in width, forming " diabasic " covellite. The plates are irregular in shape and have low interference colors, in contrast to the high colors of the laths. Where the covellite laths are plentiful, the inclosing chalcocite is isometric, otherwise it is orthorhombic.

The " diabasic " covellite is the counterpart of that which has been found [8] to be formed by ex-solution from an earlier-formed solid solution of covellite in chalcocite. Since this covellite also occurs in isometric chalcocite, which in turn must contain eight per cent. or more covellite in solid solution, it is interpreted as hypogene covellite that has been formed above a temperature of 91° C. and has unmixed upon slow cooling to form the covellite laths. The presence of this unmixed covellite is also a further indication of the hypogene origin of the including chalcocite.

Enargite.—Enargite occurs as bunches of pure mineral of hand specimen size or as small grains admixed with the other minerals. Under the polarizing microscope the massive variety is seen to be made up of large grains surrounded, for the most part, by minute grains of varied optical orientation, resembling arkose in texture. The enargite has clearly replaced limestone, numerous embayed residuals of which are included in the enargite grains.

Luzonite.—The pinkish variety of enargite, luzonite, occurs in small grains and veinlets inclosed in chalcocite. The veinlets appear to be later in age than the chalcocite, although the possibility is recognized that veinlets of a mineral may be left as residuals in chalcocite that has replaced it.

Bornite.—Bornite occurs in minor amounts as isolated areas inclosed in chalcocite. Some of it incloses small areas of chal-

[8] Bateman, Alan, and Lasky, S. G.: *op. cit.*

cocite. Part of the bornite, at least, is earlier than chalcocite that embays it. Some appears to be contemporaneous with the chalcocite.

Two kinds of bornite are present; one, the usual isotropic variety, and the other, an unusual anisotropic variety. Both exhibit the same color, behave similarly to etch reagents, and resemble each other in all respects, save that the one is isotropic and the other anisotropic.

Other Minerals.—A few small specks of pyrite and chalcopyrite and one grain of galena, were observed. Their relationships to the other minerals could not be determined. No silver minerals were observed. The silver content of the ore must, therefore, be present in solid solution with the copper minerals.

OXIDATION AND ENRICHMENT.

There is no evidence of any supergene enrichment of the ore. Hypogene sulphides outcrop on the surface. Oxidation is almost lacking; only a thin veneer of copper carbonates exists. Even stains of "limonite" are scarce. The deposit is not favorably situated for the preserval of zones of oxidation or enrichment. It lies near the bottom of a great valley that has been widened and deepened by vigorous glacial erosion (Fig. 1). The glacier itself has only recently receded from the site of the deposit, and from the outcrop one may see the retreating ice mass less than four miles upstream, where it fills the upper part of the valley to a depth of hundreds of feet. Any oxidized or enriched zone that may have existed has been eroded away and the time that has elapsed since the exposure of the outcrop to the air has been too short, and the climate too cool, for new zones to have been formed.

SIMILARITY WITH KENNECOTT DEPOSITS.

The character of the ore, its mineralogy, and its localization in the lowermost beds of the Chitistone limestone are all similar to the ore occurrence at Kennecott. As at Kennecott, the ore is quite unique; it consists chiefly of massive hypogene chalcocite and the chalcocite itself is unusual in that much of it is coarsely

granular and the high-temperature isometric variety is present; ex-solution forms of covellite in chalcocite are present; copper-iron sulphides are scarce; pyrite is almost lacking; and quartz is absent. At both places, metallization consisted of copper, silver, and sulphur with minor amounts of arsenic, a little iron, and a noteworthy absence of silica.

The similarities of these two unique deposits are so striking that the conclusion is inescapable that they must have been formed at the same time, from the same source, and by similar processes, and thus have a common ancestry. Still other offsprings of the same metallization occur as unimportant deposits scattered over this region. These deposits indicate that this peculiar metallization was quite widespread, remarkably uniform in composition, and almost entirely restricted to the lower beds of the Chitistone limestone.

ORIGIN OF DEPOSIT.

The Glacier Creek deposit is shown, by the presence of isometric chalcocite, unmixed covellite, enargite, and bornite, to have been formed from hypogene solutions at a temperature above 91° C. The mode of emplacement was chiefly by replacement of the dolomitic limestone, and some of the covellite and chalcocite may have been deposited as colloids. The solutions apparently were sufficiently attenuated to penetrate minute cracks.

As to the source of the solutions and of the introduced metals, the deposit and its surroundings offer no conclusive evidence. It is customary, in keeping with the modern conceptions of the origin of ore deposits, to associate the solutions and metals genetically with some nearby intrusive or magmatic reservoir. In the case of the Glacier Creek deposits there is no immediately adjacent intrusive. The nearest one, a light colored quartz-diorite porphyry, lies about ten miles to the west. It may be a possible source of the copper and the solutions. The gold quartz deposits of the Nizina district are believed to be genetically connected with it, and the Kennecott deposits may possibly be connected with another part of the same intrusion. However, at Kennecott, a light-colored dike, an apophyse of this intrusive, cuts diagonally

across one of the copper veins and is later than the ore. Consequently, if the Glacier Creek and Kennecott deposits are of the same age, as seems reasonable, the Glacier Creek ore must also be earlier than the dikes that extend out from the main intrusive mass. This fact, combined with the lack of iron and silica in the deposit, and the distance of the deposit from the intrusive, offers difficulties in the acceptance of a genetic connection between the ore and the quartz-diorite intrusive.

The only definite evidence, therefore, is that the solutions were hot and hypogene, that they were of uniform composition over a wide area, and that the deposition of the metals was confined largely to the lowermost beds of the Chitistone formation.

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DISCUSSION AND COMMUNICATIONS

THE ANNOTATED BIBLIOGRAPHY OF ECONOMIC GEOLOGY.

Sir: May I voice a note of thanks to Dr. Waldemar Lindgren and his collaborators for furnishing economic geologists with the "Annotated Bibliography of Economic Geology." Each number covers the field of the literature of "Economic Geology" more broadly and more satisfactorily and so becomes a more valuable tool for our profession. The bibliography is perhaps particularly valuable to the professional economic geologist, who has less time to read all the journals devoted to geology and mining than the college professor, and in consequence finds the digests most advantageous in deciding what original articles he may later read. In our office, at least, we depend upon the bibliography, before entering a district with which we are not familiar, to furnish us with references of all the literature pertaining thereto.

To my surprise I find that a number of mining engineers and geologists are unacquainted with the bibliography's excellence, and I am writing the above in the hope that its usefulness may be brought to the attention of others who may profit from its use.

SYDNEY H. BALL.

REVIEWS

Studies of Geophysical Methods, 1928 and 1929. By L. GILCHRIST, J. B. MAWDSLEY, AND OTHERS. Pp. 227, figs. 66, maps, 11. Geol. Survey of Canada, Mem. 165 (Ser. 2266), Ottawa, 1931. Price, 45 cts.

The volume consists of a series of succinct technical reports of studies in the application of the methods or in research in connection with special theoretical problems. It does not pretend to be a well-rounded finished survey or report on the geophysical methods of prospecting, but is essentially a case-book reporting the results of many separate investigations. The Radiore, Schlumberger, and Swedish-American companies made surveys and reports on the sphalerite-chalcopyrite-pyrite deposit of the Abana mine as if each had been making a routine commercial survey, and the Survey geophysicists report on the reports. Eve, Keys, Schwartz and others report the results of important fundamental studies at Mammoth Cave on the penetration of strata by electro-magnetic fields and on the resistivity of strata *in situ*, also on other studies in the field application of electric methods. Gilchrist reports on a series of electric investigations at the Abana, Falconbridge, and Errington mines. Miller, French, and Wilson report on torsion balance and magnetic surveys of the Hull-Gloucester and Hazeldean faults.

The volume is meaty and a notable contribution to the technical literature of geophysics. The engineer or geologist or layman who is not already an advanced geophysicist in general will find the volume too advanced. The elementary student of geophysics in general will find the volume of value only as his instructor assigns him selected references in it. The studies at Mammoth Cave may prove of value to the petroleum geophysicist in connection with improvement of his use of the electrical methods and to the miner in connection with signaling between the surface and the subsurface workings. The volume otherwise is primarily of interest only in connection with mining geophysics.

The volume is of a type of which we need many more. The present literature of applied geophysics consists all too much of theory by physicists who are poorly familiar with actual field surveys with the methods. of theory by commercial geophysicists who are studiedly careful not to tell too much, of carefully selected successful cases of the application of the methods, chosen by commercial geophysicists to show how well their methods work, of over-optimistic statements of what the methods will do and not of what the methods have actually proved themselves capable

of doing, of the laboratory determination of the physical constants of hand specimens (in contrast to the corresponding geophysical constants of the formations *in situ*), and all too little of careful impartial frank case reports of the actual applications of the methods with statement of the failures and uncertainties as well as of the successes, and all too little of the actual determination of the geophysical constants of formations *in situ*. This volume, which comprises impartial reports by government and university geologists and geophysicists, discussion of theory in the field as it were, and some determination of geophysical constants, is therefore a most welcome contribution to the literature of geophysics.

DONALD C. BARTON.

German-English Geological Terminology. By WM. R. JONES AND A. CISSARZ. Pp. xvii + 25, cloth. Thos. Murby & Co., London, 1931. Price, 12 s 6 d.

Because technical dictionaries do not give the specific meanings of many geological terms, the authors of this little volume have hit upon the plan of giving readers the meaning of corresponding terms in German and English by translating almost literally from one language into the other paragraphs in which the terms are employed. The corresponding terms in the two paragraphs are italicized so that there can be no mistake about them, even though the construction of the sentences in which they are used is different.

There are 14 chapters in the book, each devoted to terms employed in some distinct phase of geology, as denudation, paleontology, crystallography, metamorphism, ore-deposits, etc., and 5 appendices containing lists of abbreviations in the two languages, German and English mineral names, and conversion tables for measures and weights. English and German indexes of nearly 2400 geological terms direct the reader to the pages on which the terms are used.

The reviewer feels that the book should be of great use to English students who are a little weak in German and vice-versa, because of the greater ease with which the meanings of the terms in the respective languages are absorbed when employed in sentences, than is the case when the same terms, isolated from their contexts, are defined in dictionaries.

W. S. BAYLEY.

Geology and Ore Deposits of Rouyn-Harricanaw Region, Quebec. By H. C. COOKE, W. F. JAMES, AND J. B. MAWDSLEY. Pp. 314, pls. 3, figs. 28, map. Canada Dept. of Mines, Geol. Surv. Mem. 166. Ottawa, 1931. Price, 45c.

Even before the discovery in 1923 of copper ore on the Horne property which resulted in the development of the Noranda Mine and feverish

prospecting throughout the district, the Dominion Survey geologists had entered the region and have since been publishing reports from year to year. The present memoir coördinates the data hitherto published, adds much new material, and offers a comprehensive interpretation of the geology of some 4000 square miles of complex pre-Cambrian rocks. The descriptions of formations include a condensed treatise on the formation of pillow lavas and associated structures and their usefulness as indicators of the attitudes of flows.

The major axes of folding in the Keewatin lavas and in the overlying Timiskaming sediments have been worked out by careful structural methods, though the numerous dip and strike observations listed in the text would have been more useful to the reader if they could have been plotted on the map. Those who have followed the controversy over the origin of the Cobalt series (Huronian) will read with interest the description of striae below its base and the authors' hearty support of Coleman's theory of glacial origin for the conglomerate.

The separation of the intrusives into three age-groups dated by Timiskaming deposition and post-Timiskaming folding is a notable forward step in the geology of the region, and the authors' evidence that the "younger gabbro" is earlier than the Huronian sediments merits attention since several writers have considered this rock Keweenawan and related to the basic intrusives of Cobalt and Sudbury.

Throughout the district are gold-quartz veins and replacements similar in a general way to those of Ontario; several of them are of commercial value. There are also molybdenum deposits of pegmatitic affiliations, but so far, the most important ores economically have been the "potato-shaped" sulphide masses carrying gold and copper. In these, pyrite-pyrrhotite mineralization was accompanied by formation in the wall-rock of quartz, actinolite, and epidote, and was followed by deposition of chalcopyrite (and sphalerite) with strong chloritization. So many examples of a sequence of this sort have been shown to represent successive stages in a single prolonged epoch of mineralization that the authors' conclusion that the chalcopyrite of the Rouyn district is "much later" than the iron sulphides and from a separate source can hardly enjoy general acceptance without evidence more compelling than is presented in the memoir. The change, although abrupt, in the mineral phases deposited is not beyond explanation on the basis of changed chemical composition in the solutions from an original source, or changed temperature conditions at the point of deposition. It would be reasonable to place more weight upon the habitual close association of the iron and copper sulphides than upon the local absence of one or the other of the phases, and even a period of dike intrusion that is held to separate the two stages is not necessarily evidence of a significant hiatus in time.

Quite apart from theoretical considerations, the memoir will be not only a valuable aid to development and prospecting in a comparatively new district but an important contribution to the knowledge of the Canadian Shield and its ore deposits.

TIMMINS, ONTARIO.

H. E. MCKINSTRY.

A Descriptive Petrography of the Igneous Rocks. Vol. I. Introduction, textures, classifications, glossary. By ALBERT JOHANNSEN. Pp. 267, figs. 145. Univ. of Chicago Press, 1931. Price, $4.50.

A brief introductory chapter on the terminology used in connection with igneous rocks leads the reader into Chapters II and III, which deal with the constituents, and the structures and textures, of igneous rocks. This part is included within the short space of 50 pages—too brief, in the opinion of the reviewer, for so important a part of the subject. The reader is greatly assisted, however, by unusually excellent photomicrographs.

The next 107 pages are devoted to a presentation of some 26 classifications of igneous rocks—a number perhaps necessary for historical record but not very digestible to the student. Had there been fewer of these and more critical discussion of them, the book would be of wider interest.

The 87 pages of appendices constitute a valuable part of the book. The glossary of petrologic terms will be of particular interest to the student, especially since they are accompanied by valuable references. An unusual feature of this part is that the descriptions of many textural or structural terms are clarified by accompanying illustrations.

The book is nicely gotten up and should prove of value to the student when accompanied by the forthcoming second volume, which will be awaited with interest.

ALAN BATEMAN.

Witwatersrand Mining Practice. By G. A. WATERMEYER AND S. N. HOFFENBERG. Pp. 895, figs. 489, pls. 2. Transvaal Chamber of Mines, Johannesburg, 1932. Price, 45/.

An outstanding contribution to mining practice, profusely illustrated. It treats of the history of the gold discovery, the geology, prospecting, and all phases of mining, including sanitation, labor accidents, legislation, economics, and mine accounts. It is more than Rand mining practice; it is almost a textbook on mining. It should be studied by all mining men.

Copies of books mentioned under "Reviews" or under our "New Book List" (see advertisement page) may be purchased through our Journal Bookshop by writing to W. S. Bayley, University of Illinois, Urbana, Ill.

BOOKS RECEIVED.

By

DAVID GALLAGHER.

Bibliography of South African Geology for the Years 1926–1930 Inclusive, Author's Index, by A. L. HALL. Pp. 160. Union of So. Afr. Geol. Surv. Mem. 27. Pretoria, 1931. 5/.

High-Calcium Limestone Near Morris, Illinois, by J. E. LAMAR AND H. B. WILLMAN. Pp. 26, maps, figs. Illinois Geol. Surv. Rept. of Inves. 23. Urbana, 1931.

Illinois Petroleum: Mud-Fluid Materials in Eastern Illinois, by J. E. LAMAR, and **Petroleum Developments in Illinois in 1929 and 1930,** by A. H. BELL AND E. T. BENSON. Pp. 16. Illinois Geol. Surv. Press Bull. Ser. 20, July 11, 1931.

Mineral Resources of the United States, 1930, Summary. Statistics assembled by M. B. Clark from data furnished by specialists of the Division of Mineral Statistics. Pp. 120. U. S. Bur. of Mines. Washington, Nov. 9, 1931. 20 cts.

Gases That Occur in Metal Mines, by D. HARRINGTON AND E. H. DENNY. Pp. 21. U. S. Bur. of Mines, Bull. 347. Washington, 1931. 5 cts.

U. S. Bureau of Mines, 21st Annual Report of the Director, for year ending June 30, 1931. Pp. 61. Washington, 1931. 10 cts.

Government Railways of Japan. Geotechnical Committee, Bull. 1. Pp. 338, figs., pls. Tokyo, 1931. Contains proceedings, papers, reports, and abstracts, pertaining to soil science with special reference to railway engineering.

The Queen of the Sciences. By E. T. BELL. Pp. 138. Williams and Wilkins Co., Baltimore, 1931. Price, $1.00. A popularly written introduction to mathematics, outlining its philosophy, method, and the part it plays in intellectual and scientific pursuits. This is the first of a series of 20 books to be published in collaboration with the Century of Progress Exposition in Chicago in 1933.

Potash Possibilities of Nova Scotia. By A. O. HAYES. Pp. 147, maps 15, sketches 11, pls. 38. Nova Scotia Dept. Pub. Works. Annual Report of the Mines, 1930, part 2. Halifax, 1931. Good material abominably edited.

Investigations of Mineral Resources and the Mining Industry (Canada), 1930. Pp. 82, figs. 2, pls. 5. Canada Dept. Mines, Mines Branch, No. 723. Ottawa, 1931. Contains: Bituminous sands of northern Alberta, 1930 operations, by S. C. ELLS; Possible industrial applications for bentonite, by H. S. SPENCE AND M. LIGHT; Petroleum

and gas, eastern Canada, by E. H. WAIT; Diatomite, character and uses, by V. L. EARDLEY-WILMOT; Possibilities for utilization of Canadian-produced copper in home industries, by A. H. A. ROBINSON AND W. H. LOSEE.

Chrysotile Asbestos in Canada. By J. G. Ross. Pp. 146, tables 21, pls. 34, figs. 8, charts 6. Can. Dept. Mines, Mines Branch, No. 707. Ottawa, 1931. Price, 25 cts. Asbestos mining and milling methods and costs, uses and manufacture of asbestos products, asbestos mines and prospects in Canada.

Minerals of Connecticut. By J. F. SCHAIRER. Pp. 127, figs. 14. Conn. State Geol. and Nat. Hist. Surv. Bull. 51. Hartford, 1931. Elementary mineralogy, Connecticut occurrences and descriptions of over one hundred minerals, origin of rocks and minerals, and descriptions of Connecticut mineral localities.

A Barite Deposit in Hot Springs County, Arkansas. By B. PARKS AND G. C. BRANNER. Pp. 59, pls. 6, 1 fig., tables 5, maps 3. Ark. Geol. Surv., Information Circular 1. Little Rock, 1932. Price, $1.00. Location, quality, origin, geology, description of prospects, tonnage estimates.

Surface Waters of Tennessee, with a chapter on Flood Conditions. By W. R. KING. Pp. 165, tables 29, pls. 21, figs. 35. Tenn. Dept. of Educ., Div. of Geol. Bull. 40. Nashville, 1931. Methods of surface water investigation, Tennessee floods, gaging-station records.

Preliminary Report on the Artesian Water Supply of Memphis, Tenn. By F. G. WELLS. Pp. 34, pls. 2, figs. 7. Tenn. Dept. of Educ., Div. of Geol. Bull. 42. Nashville, 1931.

Methods and Apparatus Used in Determining the Gas, Coke, and By-product Making Properties of American Coals. By A. C. FIELDNER, J. D. DAVIS, R. THIESSEN, E. B. KESTER, AND W. A. SELVIG. Pp. 107, illus. 53. U. S. Bureau of Mines Bull. 344. Washington, 1931. Price, 40 cts.

The Grand Coulee. By J. H. BRETZ. Pp. 87, figs. 53, stereoscopic views 8, 1 map. American Geographical Soc. Special Publication No. 15. New York, 1932. Beautifully published account of this astounding scenic feature and its origin, which is attributed to great floods from melting continental glaciers.

Dados Hydrographicos, 1929 (Brazil). Pp. 152. Serv. Geol. e Min. do Brasil, Bol. 54. Rio de Janeiro, 1931.

Contribuição á Geologia do Estado de Minas Geraes, Brazil. By D. GUIMARÃES. Pp. 36, pls. 5. Serv. Geol. e Min. do Brasil, Bol. 55. Rio de Janeiro, 1931. General geology of the diamond, iron, and manganese regions.

SCIENTIFIC NOTES AND NEWS

E. L. DeGolyer has been appointed representative of the American Association of Petroleum Geologists in connection with the International Scientific Expedition to the West Indies.

E. H. Sellards, of the University of Texas, who has been acting director of the Bureau of Economic Geology, has now been appointed director.

M. E. Wilson and H. C. Cooke, of the Geological Survey of Canada, recently delivered a series of lectures on geology at Queen's University, Kingston, Canada.

C. H. Wegemann is engaged in work at the Johns Hopkins University, Baltimore, Md., and has also been lecturing there on petroleum geology.

Robert C. Williams, who has been doing geological work for the Anglo-Chilean Nitrate Company in Chile, is now living in Brooklyn, N. Y.

Albert C. Seward, of Cambridge University, lectured at the Smithsonian Institution, Washington, on March 30, on the subject of Plant Records of the Rocks.

Dean E. Winchester, of Denver, Colorado, is engaged in mapping the geology of the New Mexican oil fields.

D. F. Kidd, of the Canada Geological Survey, has gone to LaBine Point, Great Bear Lake, to continue his study of the new uranium silver deposits of that region.

B. S. Butler, of the University of Arizona, has been appointed an associate editor of this journal.

Arthur Holmes, Professor of Geology at the University of Durham, England, gave an illustrated address on the Thermal History of the Earth, before the Washington Academy of Science on April 7, and at Yale University on April 14.

The American Association of Petroleum Geologists has elected the following officers: President, F. H. Lahee; Vice-President, R. T. Riggs; Second Vice-President and Secretary-Treasurer, W. B. Heroy; Third Vice-President and Editor, Ralph D. Read.

The American Society of Economic Paleontologists and Mineralogists: new officers are: President, G. D. Hanna; Vice-President, J. A. Waters; Secretary-Treasurer, Gayle Scott; Editor, R. C. Moore.

The American Society of Petroleum Geophysicists: new officers are: President, Paul Weaver; First Vice-President, G. H. Westby; Second Vice-President, John H. Wilson; Secretary-Treasurer, T. F. Weinzierl; Editor, L. W. Blau.

J. Claude Jones, professor of geology and dean of the Mackay School of Mines of the University of Nevada, died March 2, at Reno.